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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Visual Protection and Enhancement

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.379

VISUAL PROTECTION AND ENHANCEMENT

Papers presented at the Aerospace Medical Panel Symposium held in Athens, Greece, 22—24 April 1985.

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*Issued in Classified Publication CP-379 (Supplement)

OPENING ADDRESS

by

Lieutenant General D.Apostolakis
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Greece

Mr Chairman, ladies and gentlemen,

I welcome you to Athina, the city of Athena - goddess of wisdom - as well as to the area where the legend of Ikarus was created and Hippocrates was born and lived.

The Greeks from ancient time have considered human wisdom as a gift of the gods and have always honored scientists as special men gifted by nature.

In line with this tradition, the Greek Airforce has made every effort to create the best possible environment and working conditions for the scientists of the AGARD Aerospace Medical Panel attending this Spring meeting.

The topics of both symposia are of great interest to the Airforce. The Hellenic Airforce, as you can realise from the large participation of our flight surgeons, fighter pilots, and flight engineers, finds it of the same importance as well.

Perfect vision is the most one can demand from a fighter pilot. Nevertheless, modern warfare tactics demand super-human vision as, for example, night vision like that of the owl, as well as protective means against blinding laser beams. So, the presentation of your research work on "Visual Protection and Enhancement" is eagerly anticipated.

Future fighter aircrew will have to combine the strength of mind of a scientist and the muscular strength of a wrestling champion in order to be able to exploit all fighting capabilities of the modern high performance aircraft and at the same time, sustain the rapid onset and prolonged action of high G forces.

What are the medical criteria for selecting future champions among thousands of candidate pilots? Are there any predictive physical characteristics? And once selected and trained, what is the optimum physiological training program to keep them in the highest possible fitness and fighting readiness?

Some of these and other relative questions will hopefully find practical and applicable answers from the presentations of your research work during the second symposium on "Medical Selection and Physiological Training of Future Fighter Aircrew".

"Symposium" is an ancient Greek word meaning drinking together. Our ancestors, at the time of Plato and Socrates, very probably on this same spot that we now find ourselves, used to philosophize staying awake all night while applying the golden principle of never overdoing.

Continuous sharing or otherwise co-drinking of thoughts, ideas and knowledge for one week may prove too heavy for most of our minds, so we have arranged for a relaxation break with a short tour through a picturesque route to ancient Epidayros and the historic town of Nayplion.

In closing, I would like to stress that the Greeks are peace loving people because they have had the bitter experience of numerous wars during the three thousand years of their history. But, they also know that the best deterrent to war is a very strong defence. Your specialty, aerospace medicine, through its contribution to the improvement of defence is actually helping in stabilising peace.

I wish you success in your efforts and a pleasant stay in Greece.

TECHNICAL EVALUATION REPORT
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1. INTRODUCTION

The Aerospace Medical Panel Symposium on Visual Protection and Enhancement was held at the Zappeion Exhibition Hall, Athens, Greece from April 22 to 24, 1985. Authors from five NATO countries presented 25 papers.

2. THEME

The theme of the symposium recognised that vision is the pre-eminent sensory channel through which the aviator obtains information necessary for the control of his aircraft and the execution of his operational role. Recognising this importance all reasonable and practical means of enhancing and protecting vision should be adopted. The papers selected for this symposium considered not only systems for visual protection and enhancement but also addressed the basic physiological and pathological mechanisms underlying existing and future solutions.

3. PURPOSE AND SCOPE

The purpose of this symposium was two-fold. Firstly to discuss current and future technologies for the protection of the eyes of aircrew against hazards from impact and non-ionising radiation and to address the problems of integrating any protective devices within the cockpit. Secondly to consider means of enhancing vision by new intra and extra ocular lenses, avionic displays, night vision goggles (NVGs), forward looking infra red (FLIR), low light television (LLTV) and helmet mounted displays (HMDs) and, again, the problems of their integration within the cockpit and with each other.

The scope of the symposium was both broad and deep and encompassed multi disciplinary experts from military establishments, hospitals, universities, industrial research laboratories and the aerospace industry. The expertise of the participants included basic visual sciences, ophthalmology, physics, psycnology, cockpit design, lighting, aircrew equipment assembly integration and operational flight problems. The topics that were discussed were wide ranging including the physiology of night vision, equipment design and development, threat analysis, operational requirements and the correction of ametropia and pathologically induced visual effects from impact and non-ionising radiation. The problems of cockpit design and lighting were also considered.

4. SYMPOSIUM PROGRAMME

The symposium consisted of four sessions, each session addressing different aspects of visual protection and enhancement.

The first session concentrated on 'Devices for Visual Enhancement and their Integration' and mainly, dealt with NVGs, although papers were also presented dealing with FLIR systems, HMDs and the operational aspects of night flight.

The second session was entitled 'Visual Standards and Corrective Devices' and papers were presented on the acceptability of various ocular disabilities in flight. The acceptability and flight worthiness of contact lenses, new spectacle lens designs and intra ocular lenses were also discussed.

The third session 'Ocular Protective Devices' was concerned with ocular protection against the hazards of laser and nuclear non-ionising radiation and also with protection against impact and ballistic fragments. This session discussed both the benefits and deficits inherent in current and proposed protective devices.

The fourth session on 'Cockpit Integration' was brief consisting of, only, two papers. The first paper discussed the visual difficulties which can arise in the integration of head up displays with windscreens and the second paper emphasised the necessity of relating cockpit displays to human factor requirements.

5. TECHNICAL EVALUATION

a. Devices for Visual Enhancement and their Integration

The first paper presented this session (Paper No 3 Haidn) was based on experience gained in low level helicopter flights over a period of eight years. The author detailed the problems in maintaining intensive operations over several days, against a highly mobile enemy employing sophisticated electronics and weaponry. He discussed the relative advantaves and disadvantages of night flight, using the dark adapted naked eye, LLTV, FLIR and NVGs. He concluded that NVGs were the simplest and most cost effective solution. NVGs however, had many disadvantages. These included

relatively poor resolution, restricted field of view of 40 degrees, difficulties with perspective at low level and physiological and psychological stress. The primary physiological problem was caused by the mass of the NVGs causing strain and spasm of the neck muscles under extreme conditions, particularly with aircrew having pre-existing disease of the cervical spine, such pathology could be exacerbated. He was particularly concerned with the invertebral discs and also, presumably, conditions such as cervical spondylosis. He considered psychological stress to be a major problem, this stemmed from the necessity of maintaining constant vigilance to avoid collision, without any possibility of even brief periods of relaxation. This intense concentration when coupled with disturbances in the diurnal/nocturnal cycle and sleep deprivation caused increased tension and stress, which often manifested itself in behavioural changes and increased reliance on colleagues. The author discussed the problems associated with vibration and its attendant loss of acuity and the difficulties associated with cockpit lighting to avoid glare in the NVGs. He considered that fluorescent numerals lit by ultra-violet to be preferable to the generally preferred complementary blue/green lighting with red filtration. In all this paper presented a valuable insight into the problem of night flight from a pilot's standpoint.

The second paper presented in this session (Paper No 1 - Verona) gave the historical progression in devices to improve night vision commencing with the searchlight, perhaps fitted with a covert infra-red filter, to third generation NVGs. The author explained that the first generation tubes were efficient having a gain of approximately 40,000X for a three stage tube and possessed a resolution of 30-36 line pairs per millimetre (LPM). They were robust and long lived but suffered from blooming by bright light sources. The second generation intensifiers were smaller and lighter, these twin advantages being due to the adoption of a micro channel plate (MCP). The MCP reduced the blooming problem, but the gain is lower and the service life of the tubes is reduced. The third generation intensifiers employ a gallium arsenide photocathode and have the twin advantages of sensitivity, which permits their use under starlight conditions and longevity. The resolution is, also, better than the second generation tubes being at 36 LPM similar to the performance of the bulky first generation tubes. The author did not foresee the emergence of a still further improved fourth generation intensifier.

The third paper presented (Paper No 2 Bohm) discussed the two technologies which either amplify light in the near infra-red 600-900nm or those which amplify thermal radiation predominantly in the range 8-12 μm. The author commenced with a brief review of the performance of the human eye in terms of light sensitivity and resolution and continued into ocular modulation transfer function characteristics and the effects of atmospheric transmission. He extended his paper with a review of the performance of NVGs, LLTV and FLIR presenting a useful table comparing the advantages and disadvantages of the three technologies. He then gave a description of helicopter trials of pilot vision systems incorporating helmet mounted sights and displays coupled with a helmet position sensing device. The displays were driven by either LLTV or FLIR sensors which were mounted on a steerable platform slaved to helmet position, thus following the line of sight. Retinal rivalry problems were not encountered with this combination under twilight conditions. After a review of other systems the author concluded that pilots might find that the optimum system was a steerable wide field of view FLIR coupled with the use of NVGs. In short, this was a comprehensive and interesting presentation of night flight using sensors from the dark adapted eye through LLTV to FLIR.

The fourth paper (Santucci) amplified our understanding of the visual problems created by the use of helmet mounted displays (HMD), describing the results of laboratory and flight testing using a HMD mock up. Studies such as this are of great value in determining the ability of the pilot to fuse dissimilar images presented to the right and left eyes. When fusion is absent, attention alternates between the eyes in response to interest or contrast. At night the problem of retinal rivalry is reduced but other problems may arise. The author showed that stereoscopic and angular acuity was reduced in laboratory testing and that pilots in flight tests misjudged height, which he attributed to the different density in front of each eye (Pulfrich phenomenon). His most important conclusion was that pilots could use the HMD mock up successfully, albeit with reduced performance, in some manoeuvres. He concluded however, that more studies and further equipment development were necessary.

The fifth and sixth papers (Breitmaier presented by Reetz and Genco presented by Susnik) provided valuable insight as to the state of the art in NVG compatible lighting and to the latest NVG developments. Author Breitmaier discussed the relationship between spectral response of intensifier tubes and the various lighting solutions that have been proposed and related these to the photopic spectral response of the eye. This is of considerable interest as blue/green lighting systems reduce cone acuity whereas yellow/green systems would improve the acuity of aircrew not wearing NVGs and, would, by approximating the hue of the NVG phosphor, be less distracting for NVG wearers. The author also presented a review of luminance levels of cockpit lighting and displays which would be compatible with ANVIS NVG radiances of external scenes. He cited the example of a starlit defoliated tree as being, by virtue of its low reflectivity, a particularly hazardous obstacle whose detection must not be degraded by over bright cockpit lighting.

Author Genco also discussed NVG compatible lighting systems and described the concept of shared apertures where a pinhole aperture is placed in the centre of the minus blue filter on the intensifier tubes thus allowing a small amount of blue/green cockpit lighting to be seen without, causing the automatic gain control to function and thus preventing low luminance external targets being seen. This is one solution to the problem of reading instruments with NVGs focussed at infinity. Although most NVGs now permit a 'look under' view or permit vision through combiner plates (Cats Eyes).

Author Genco also described an ingenious system of injecting collimated flight data onto a beam-splitter mounted in one NVG barrel, which he styles an NVG head up display (HUD). A similar result could be obtained by using NVGs already equipped with beam-splitter optics such as Cats Eyes. Cats Eyes and other NVGs, such as those developed by the Air Force Aeromedical Research Laboratory with the intensifier tubes angled can increase the field of view by presenting right and left monocular fields with a central binocular overlap. If the coatings are suitably graduated the visual distraction caused by the apparent separate right and left fields with a bright overlap area in the middle, should not be evident.

The seventh and eighth papers (Simmons and Price) were both presented by Col Price. Author Price gave what was essentially an overview of the night vision devices used in military helicopters and their aeromedical aspects. Firstly he reinforced the performance characteristics of the second and third generation NVGs as previously described by Verona. He described the results of investigations into contrast sensitivity, depth perception and reduction in dark adaptation for second generation tubes. He postulated that contrast sensitivity and resolution would improve but he expected little, if any, improvement in depth perception or reduction in dark adaptation. The author described the integrated helmet and display sighting system (IHADSS). In a similar fashion to that described by Bohm, IHADSS presents slaved FLIR imagery to the pilot from a helmet mounted cathode ray tube (CRT) and a see-through combiner. The imagery has a FOV of 40 degrees horizontally and 30 degrees vertically and a resolution similar to that of third generation NVGs. It also provides flight data symbology. The author was, as yet, unable to comment on the problems of eye dominance and retinal rivalry or integration with other head mounted equipment.

Author Simmons described an ingenious device which is in essence a spectacle mounted HUD which is compatible with NVGs. The left spectacle lens incorporates 4 aspheric mini mirrors each of which can present a 3 digit number derived from a segment light emitting diode (LED) array. The right lens derives information from a symbol generator which can present a dynamic pictorial representation of pitch and roll. The spectacles are fully adjustable so that the information presented to both eyes can be simultaneously perceived. As worn, the micro spectacle HUD is seen against the green imagery of NVGs which are worn in front. The device is also useable without NVGs when the symbology is viewed against the night sky. The author described the advantages and disadvantages of the system and also proposals for its improvement. He concluded that, with development, the micro HUD would have great utility for selected mission scenarios.

The tenth paper (Bull) whilst accepting that gimballed sensors have been refined considered that what was needed was a simple system to which a daytime pilot could rapidly become accustomed. In his opinion NVGs provided the answer as they had an excellent look around capability, combined with an acceptable field of view and twin tubed NVGs provided failure redundancy. NVGs do have the inherent disadvantages of limited sensitivity, resolution and dynamic range, coupled with the necessity to look through a canopy with a device without a true infra-red capability. The author considers that NVGs should, therefore, be complemented with FLIR imagery on a HUD using a normal complementary filter to prevent the HUD imagery being seen by the NVGs. This system provides good look around with the Cats Eyes NVGs enhanced by direct vision of the boresighted FLIR on the collimated HUD under poor meterological conditions. The differing spectral sensitivities of the two devices provided information which neither device alone could achieve.

The ninth paper (Macmillan) addressed the problems of the integration of NVGs with United Kingdom protective helmets. The criteria which he regards as essential are that NVGs must be mounted securely on a stable platform which ensures that the NVGs do not become detached due to vibration or flight manoeuvres. The mount must permit rapid and easy removal of the NVGs in an emergency. A protective shield should be provided to protect the eyes and orbits from damage, in the event of a collision. A shield must not reduce the FOV and may thus require NVGs with an increased eye relief. This increased eye relief would also permit easier integration with other visual protective and enhancement devices, such as respirators and spectacles. He then described the advantages and disadvantages of the UK Phase 1A Assembly.

b. Visual Standards and Corrective Devices.

Paper 12 in this session 'Minimum Colour Differences, Required to Recognise Small Objects on a Colour CRT' by P. L. Philips was cancelled.

The eleventh and fourteenth papers (Draeger) considered the ophthalmological problems of airworthiness and the design of new spectacles for use by presbyopic pilots. The first paper highlighted some of the anomalies in current visual standards particularly those that applied to ground staff such as air traffic control personnel. The author then discussed the problems of contact lenses, intraocular lenses, monocular vision and glaucoma. He considered that many personnel were rejected who were fit to fly and that standards may be too rigid and that each case should be decided on its merits. The second paper dealt with the problem of presbyopic aircrew who require to read charts and also see instruments in different positions such as overhead controls and lateral panels, as well as external vision at infinity. The author considers that spectacles should not only be related to the man but also the visual requirements of particular aircraft. His recommendation is for tri or quadrifocal lenses with a lateral asymmetry according to cockpit requirements.

Paper 15 (Cloherty) tackled the contentious issue as to whether contact lenses should be on general issue to aircrew. After a review of the types of currently available lenses he concluded that high water content (75%) lenses, such as Scanlens 75, were most suitable. He then described

the results of environmental trials at IAM Farnborough in which the soft lenses had behaved well in all subjects, under all the environmental stresses. Contact lenses have not been placed on general issue due to the necessity for strict observation of hygiene and maintenance procedures. These procedures may be difficult to follow when men are on detachment in the field. The author also listed the problems which may be suffered by contact lens wearers and the remedial solutions. Contact lenses would solve many problems in aviation particularly those of eye relief and FOV and may, in the future, with new lens materials requiring less maintenance, be the corrective appliance of choice.

Paper 16 (Punt) described the results of a study to determine the behaviour of a spherical perspex (PMMA) lens and an aspherical gas permeable silicone lens under increasing +GZ forces from 1 to 9G. The aspherical silicone lens proved preferable to the spherical PMMA lens, which when subjected to forces in excess of +6GZ began to decentre to an extent which would endanger vision. This paper again adds support to the use of contact lenses in military aviation, provided a satisfactory material is found.

c. Ocular Protection Devices.

The 17th paper (Zwick) gave confirmation to earlier studies that prolonged exposure to bright sunlight conditions can cause a reduction both in the rate of adaptation and in the absolute threshold achieved on dark adapatation. In his study he compared the dark adaptation in personnel after 20 hours of exposure to bright environmental conditions. One group was unprotected and the other wore one of two types of sunglasses with luminous transmittance factors of 18% and 1.3%. The protected group showed no significant improvement for central visual function and dark adaptation for a long wavelength red LED. They did however, demonstrate an improvement in absolute threshold for a green LED stimulus. This paper makes an important point in emphasising the need for sunglass protection in personnel exposed to bright ambient conditions particularly where they need to work at night without electronic aids to vision. Filters for sunglasses should attenuate across the visible band and protection must also extend to the UV(A) and UV(B) bands. Some authors now suggest that the blue wavelengths from 400-520nm should be attenuated to a greater extent than the remainder of the visible band, the peak attenuation being centred at 441nm.

The 18th paper (Farrer) gave a brief review of the ocular effects of laser exposure in terms of pulse duration, repetitive frequency and energy. The author then made a valuable contribution to the operational use of laser protective eye wear in terms of visual acceptability and the need for sufficient but not over protection which could render the source invisible and prevent retaliatory action. He therefore emphasised that any protective device must be threat orientated and produce the minimal visual deficits.

Papers 19 and 20 (Rehmann) considered the technical requirements for devices which provide protection against the ocular hazard of nuclear flash and went on to describe a German development of a liquid crystal device. The first paper was a detailed set of mathematical calculations which considered the important parameters of emitted radiation, threat criteria and atmospheric transmittance. These were related to the visual task to be performed considering the pupillary diameter, blink reflex time, ocular spectral sensitivity and flash blindness recovery times for different instrument luminances. The author then presented an interesting curve which plotted the recovery period against weapon yield for two target luminances. This paper should prove a useful aid to all who are involved in the calculation of the hazard and required level of protection in terms of density and switch time for protection against nuclear flash. The author then described a German liquid crystal shutter which consists of twin polarisers orientated at 90 degrees with respect to each other, between which is sandwiched a liquid crystal cell which, when electrically activated, can rotate the plane of polarisation of light. The light can thus be in phase with the second polariser and be transmitted, or be out of phase and grossly attenuated. The principle is very similar to that of the PLZT device. The advantages of the liquid crystal device are its low operating voltage, failure to the open state, and, unlike PLZT, the ability to fabricate large and curved devices. The current open state transmittance is 25 - 30% and the closed state density between OD3.0 - OD4.0, the closure time being 75 - 80 micro seconds. It would be interesting to compare this device with current PLZT contenders.

The 21st paper (Chisum) gave an interesting insight into the problems of developing laser eye protection for military personnel. The author explained that many laser protective devices had marginal acceptability in terms of spectral deficits and overall luminous transmittance. The problem compounds if protection is required at more than one wavelength, particularly with the use of broad band absorbing materials. Research into dynamic devices has not yet succeeded in developing a shutter which will protect against the brief (nanosecond) pulse of a Q switched laser. Her paper continued with a description of holographic filters and discussed their advantages, which she considered outweighed their disadvantages. This theme and the problem of protection against ballistic fragments was continued in the 22nd paper (Beatrice) which was presented by Wolf.

Papers 23 and 24 (Randolph and Zwick) addressed the problems of the likely visual deficits occurring as the result of battlefield exposure to directed energy sources such as laser range-finders. The first author considered the problems of foveal flash blindness in man whereas the second author extended this to small punctate lesions of the fovea of behaviourally trained monkeys. Although both experiments were performed on small samples it was interesting to note that small (92 μm) retinal spot sizes from a xenon flash in man, resulted in only minor visual deficits with a micro second pulse width, but major deficits when the pulse was widened to 500 micro seconds.

The Zwick study used monkeys and a Q switched laser, emitting a 30 Hertz pulse train. The image size was a diffraction limited spot of 25 - 50 um, delivered at near ophthalmoscopic threshold. The results of his experiment show similar changes in loss of transient contrast sensitivity from 2.2 to 38.5 cycles per degree and that recovery times across the spatial frequency spectrum occurred within 16 minutes. He did not observe any loss of contrast sensitivity after repeated exposure trials but after several months 3 of the 4 monkeys exposed demonstrated an increase in contrast sensitivity for the larger spatial frequencies. This caused the author to speculate that the loss of contrast sensitivity over months may be due to photochemical processes and new methods of vision testing in man should be developed to test both spectral and spatial resolution. If this is not done personnel may suffer injury long before it is clinically evident.

Paper 13 (Zwick) described a technique for simulating the visual deficits likely to be incurred by lasers or induced by chemical warfare antidotes, benactazine and atropine. The technique could also be used for other ocular hazards. It consists of determining the contrast sensitivity changes at selected spatial frequencies for the various stressors and using this information to modulate the spatial frequency content of digitised computer stored imagery. The author claims that this method of degrading imagery to correspond to likely visual deficits should prove a valuable combat training aid.

d. Cockpit Integration.

Paper 25 (Hulme) described the problems of parallax shift, binocular sighting confusion with ground targets and diplopia suffered by some aircrew when using a binocular HUD. Often these problems are ascribed to a bad HUD and are more frequently suffered by aircrew with good stereopsis. As HUDs have improved in quality there still remains the problem of an optical mismatch between HUD and windscreen and the author recommends that the difference between the HUD binocular vergence angle and the windscreen binocular vergence angle should not exceed the limits -0.3 milli radians to +1.0 milli radians. This may well demand tighter optical standards for windscreens.

Paper 26 (Martin) was essentially a plea for greater human factors involvement in cockpit design, particularly with the new generation of compact cockpits and multi function controls. The author postulates that some aircraft accidents attributed to pilot error may be due to a misunderstanding of aircraft generated information caused by human factor problems in the man machine interface. We must all agree that the participation of physiologists, vision experts, psychologists and others in cockpit and instrument design should improve aircrew performance and reduce the incidence of accidents from pilot error which can be ascribed to failures in man related cockpit design.

6. CONCLUSIONS

a. There is a need for further research into the optimum means of integrating the two technologies of image intensification by NVGs or LLTV with FLIR and for improvements in the presentation of the information to the pilot.

b. There is a need for further work into NVG compatible cockpit lighting, three different schemes were discussed at this meeting blue/green, yellow/green and UV lighting of phosphors. An ideal lighting system would not cause any problems with NVGs but would also not degrade naked eye visual acuity or result in other problems such as autokinesis.

c. Visual standards should not be relaxed and indeed some visual acuity standards should be tightened. Aircrew have an ever increasing visual load with new generation aircraft and displays. The disadvantages inherent with spectacles and the difficulty of integrating these with protective and enhancement devices can only compound flight problems.

d. Contact lenses have proved their flight acceptability, it now remains to discover a lens material which is comfortable, visually acceptable, capable of prolonged wear without causing pathological changes and requires minimum maintenance. Should such a lens be discovered it would be the optical appliance of choice for aircrew and may permit a relaxation of some visual standards.

e. All military personnel should wear visors or sunglasses under conditions of high luminance. The density should be related to the ambient illumination and the visual task. The advisability of attenuating to a greater extent in the blue part of the spectrum should be considered.

f. The relative merits of PLZT and liquid crystal devices in the protection of aircrew against nuclear flash should be evaluated.

g. The conference reinforced the conclusion that all military personnel should be provided with protection against ballistic fragments. All transparencies worn by aircrew should be fabricated from impact resistant polycarbonate, the only exception being corrective lenses in higher powers where the low 'V' or Abbé value of polycarbonate can cause problems with light dispersion. In these aircrew CR39 lenses should be substituted.

h. Engineers and experts in the visual disciplines should combine at an early stage in cockpit and lighting design.

7. RECOMMENDATIONS

As the technologies of visual protection and enhancement are constantly changing there is a need for further symposia on these topics. The mix of disciplines including engineering, visual science, ophthalmology, psychology and military aviation should continue.

IMAGE INTENSIFIERS: PAST AND PRESENT

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Summary

The evolution of the image intensifier is presented from the first through the third generation. Technological advancements during the past two decades, such as the microchannel plate (MCP) and the gallium arsenide photocathodes, have significantly improved the image intensifier's projected life time and performance capabilities. Improved manufacturing techniques have contributed to the intensifier's extended life and expanded performance capabilities. This continued progress attests that the image intensifier continues to be a viable sensory extension helping man achieve his goal, the conquest of darkness!

Introduction

An image intensifier is an electronic viewing device that amplifies dim ambient light reflected from objects and presents this amplified image on a fluorescent screen. An image intensifier thus provides a means of multiplying the available reflected light so it can be seen by the eye.

This paper presents the evolution of the image intensifiers from the first generation, through the second generation, to the current third generation. The theory of operation, capabilities and limitations, and performance comparisons are presented for all three generations.

Background

Some of the first night vision enhancement devices were search lights. They were simple and effective, but were cumbersome and required large amounts of energy to operate. Their biggest problem, however, was their conspicuity! Friend and foe were able to take advantage of the light. A covert night vision enhancement device was needed that could be used only by specially equipped individuals. Near-infrared viewers and near-infrared search light filters were the answers.

The high-power search lights were modified with infrared filters which blocked visible light and passed only near-infrared (700 to 1,200 nm) energy. A simple image converter tube was used to view the illuminated scene. This approach had its draw-backs as near-infrared viewers became commonplace and useable by friend and foe. A passive viewing device was needed that did not emit detectable radiation, but simply used available light. The image intensifier was the answer.

Image intensifiers are completely passive, that is, they are not detectable by the enemy. The first generation of military image intensifiers were introduced to the field in 1965. There are currently three generations of image intensifiers used by the US military, each generation representing a tremendous technological advancement. (See Figure 1.)

FIGURE 1. Photograph of first, second and third generation intensifier tubes without power supplies and potting. Only one stage of the first generation tube is shown.

First Generation Image Intensifiers

There are two major configurations of first generation image intensifier tubes: three stage tubes and demagnification tubes. The three-stage configuration is formed by

fiber-optic coupling three single-stage unity-magnification tubes to achieve the desired amplification. The demagnification configuration tubes concentrate the electron image from the photocathode to a 300% smaller phosphor screen to achieve the desired amplification.

The scene being viewed through the image intensifier device is focused on a photosensitive material, the photocathode, as shown in Figure 2. The photocathode surface emits electrons proportional to the amount of light striking it from each point in the scene. The emitted electrons are accelerated from the photocathode toward a phosphor screen by an electric field. The light emerging from the phosphor screen is proportional to the number and velocity of the electrons striking it at each point. The observer views the amplified scene image appearing on the phosphor screen through an eyepiece.

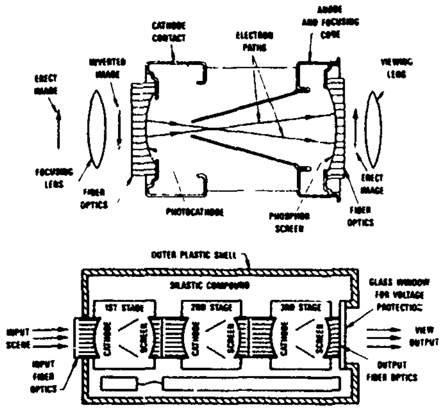

FIGURE 2. Diagrams of first generation imageintensifier tube. Diagram (a) shows a single-stage tube and diagram (b) shows a three-stage tube.

The amount of amplification, or gain, of an image intensifier is expressed as the ratio of light-in to light-out. Three-stage tubes typically have a gain of about 40,000 and demagnification tubes typically have a gain of about 2,000. Resolution limit for the first generation tube's is about 30 to 36 line-pairs/mm. First generation tubes use S-20 photocathodes. These multialkali photocathodes have an average luminous efficiency of approximately 350 microamps/lumen. The S-20 photocathode is sensitive from 400 to 850 nm, with a broad peak from 500 to 600 nm. Since the sensitivity of the photocathode extends into the near infrared, they are able to detect near-infrared sources while remaining undetectable.

The first generation intensifiers are very susceptible to blooming from bright light sources. If a bright light source appears in the device's field-of-view, the overall contrast of the intensified image is greatly reduced. If the light source is sufficiently bright, the protection circuitry in the intensifier power supply momentarily shuts down the intensifier. The peak full area luminance displayed on the phosphor screen is normally on the order of 5 to 10 footlamberts.

First generation image intensifiers are very robust and have a very long life, well into the ten-thousand hour range. Gradually the sensitivity of the photocathode diminishes and the phosphor screen shows the blackened burn marks from staring at bright point light sources. The weakest parts of the first generation systems are the battery and the oscillator module that converts the battery energy to an alternating current source for the intesifier's power supply.

<u>Second Generation Image Intensifiers</u>

Many of the first generation intensifier limitations were overcome by the second generation intensifier tube technology. The second generation image intensifier tubes are significantly smaller and lighter than the first generation. One version of the second generation tube is so small that two intensifiers may be used in a binocular head mounted system, the Night Vision Goggles. This miniaturization is achieved by the use of a microchannel plate (MCP). The MCP is used in conjunction with the photocathode to produce the required light amplification.

Light from the scene being viewed is focused on the photocathode, the same way it was in the first generation intensifier (see Figure 3). The photocathode material is also the same, an S-20 multialkali. But now, the electrons emitted from the photocathode impinge on a microchannel plate (MCP).

The MCP, shown in Figure 4, is a thin 1 mm wafer of tiny glass tubes which channel the electrons from the photocathode to the phosphor screen. As the electrons pass through the millions of glass tubes, they strike the emissive material coating the channel walls and cause the emission of secondary electrons. The tiny channels are tilted about 8 degrees so the electrons are sure to strike the walls many times on their way to the phosphor screen. Thousands of electrons exit the MCP for each electron that enters from the photocathode. The emerging electrons maintain their relative spatial position

and strike the display screen phosphor. The photocathode, MCP, and phosphor screen are in "proximity focus," that is, located very close to each other, so that the electrons do not diverge and blur the image. The phosphor screen is usually deposited on a fiber optic inverter. This inverter twists the image 180 degrees so that the scene appears erect when viewed through the eyepiece.

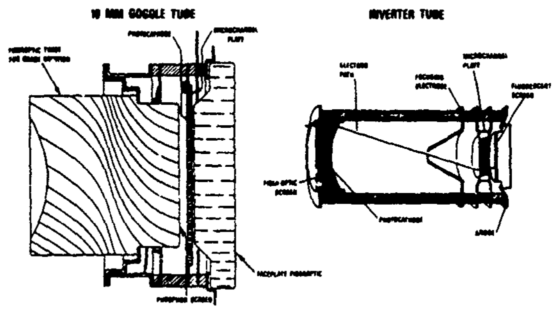

FIGURE 3. Diagrams of second generation 18 mm goggle and inverter image intensifier tubes.

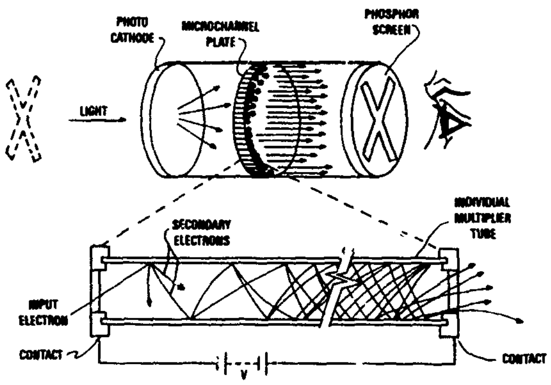

FIGURE 4. Diagram of microchannel plate (MCP) used in second and third generation image intensifier tubes.

The mass production of the MCP was the technological advancement that made the second generation possible. The MCP minimizes the contrast reduction imposed by bright light sources in the image intensifier's field-of-view. Individual channels can saturate without causing the entire device to saturate as in the first generation systems. However, local area contrast degradation still results from the localized saturation. A bright light source produces high electron densities at the MCP and phosphor screen. The high electron densities sometimes form a halo around the image of the bright light source. This halo degrades the contrast of adjacent portions of the intensified image.

An automatic brightness control (ABC) helps to protect the observer from bright flashes. The ABC does not control the number of electrons released from the photocathode; the ABC controls the MCP voltage to hold the output tube luminance to a specified level. The ABC keeps the peak display luminance between 0.3 and 0.9 footlamberts for a full range of input energy.

A bright source protection (BSP) circuit may also be incorporated in the power supply. The BSP protects the tube by limiting the number of electrons leaving the photocathode. The BPS greatly reduces the voltage between the photocathode and the input side of the MCP when the input light levels cause excessive photocathode current to flow.

The gain of the second generation tubes averages about 20,000 to 30,000--somewhat less than the first generation tubes. The second generation intensifiers require less power than their predecessors which means smaller, longer-lasting batteries. The first generation intensifier batteries are 6.75 volts and the second generation intensifier batteries are 2.7 volts.

The end of life for second generation tubes is primarily caused by ion bombardment of the photocathode. The photocathode becomes contaminated by ions given off by the MCP as it is struck by electrons from the photocathode. These ions splashing back on the photocathode cause a gradual loss of luminous efficiency. The higher the light level at the imaged scene, the more ions generated, and the shorter the life expectancy of the second generation tube. Another factor that contributes to the death of the tube is a gradual drop in secondary emission through the MCP. Generally, second generation tubes operate for 2,000 to 4,000 hours at 1/4 moonlight illumination.

Third Generation Image Intensifiers

The third generation image intensifier tubes perform much better than the first or second generation tubes under starlight illumination levels. The third generation tubes are as small as the second generation tubes, yet live as long as the first generation tubes, greater than 10,000 hours.

The third generation intensifiers, shown in Figure 5, schematically look like the second generation intensifiers. Light from the scene being viewed is focused on the photocathode. The third generation tubes, however, use a gallium arsenide photocathode bonded to a glass faceplate. The gallium arsenide photocathode surpasses the photosensitivity of the S-20 multialkali photocathodes beyond 550 nm. The sensitivity of the third generation photocathode is more than 1,000 microamps/lumen compared to the 350 microamps/lumen average of the first and second generation photocathodes.

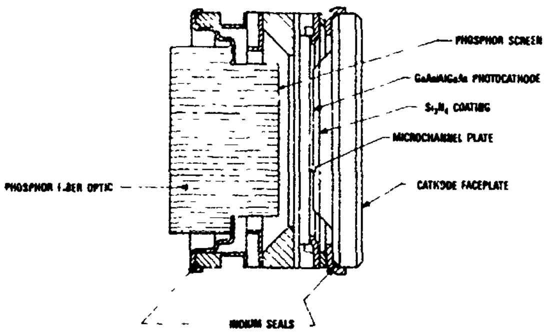

FIGURE 5. Diagram of third generation image intensifier tube.

The electrons emitted from the photocathode impinge on the MCP as they did in the second generation tubes, but now, they must pass through a metal oxide film applied to the MCP. This metal oxide film is transparent to the electrons, but not to the ions that could cause photocathode death. The metal oxide film traps the ions and prevents them from contaminating the photocathode. There are, however, some repercussions resulting from the presence of the oxide film.

The metal oxide ion barrier deposited on the photocathode side of the MCP requires the bias voltage between the photocathode and MCP to be increased from 200 to 800 VDC. This increased bias voltage requires the photocathode-to-MCP spacing to be increased to prevent arcing. The increased bias voltage raises the electric field strength which helps to maintain the focus of the electron image from the photocathode to the MCP. This gives the third generation tubes a typical resolution capability of 36 line-pairs/mm instead of 28 line-pairs/mm with the second generation tubes. The full area display luminance is also higher with the third generation devices with a range of 0.7 to 2.2 FL.

It is important to remember that there are no inherent qualities of the third generation that would lead to improved resolution. The first and second generation tubes could have the same resolution. Manufacturing and methods improvements make the difference, not the inherent operating physics.

Depositing metal oxide on the second generation's MCP would also improve life, but it would cause a 30% decrease in the signal-to-noise ratio. This decrease in the signal-to-noise ratio is unaffordable in the second generation technology but affordable in the third generation technology. One minor draw-back of the increased photocathode to MCP spacing is an increase in halo size from bright light sources when compared to second generation performance.

The third generation intensifiers with their gallium arsenide photocathodes are more usable during lower light levels than the first and second generation intensifiers. The gallium arsenide extends the tubes' spectral sensitivity range to 950 nm (see Figure 6), a region where near-infrared radiation from the stars is plentiful. The photon rate is five to seven times greater in the region of 800 to 900 nm, where the third generation photocathode sensitivity peaks, than in the visible region in the neighborhood of 500 to 600 nm. The increased luminous efficiency of gallium arsenide is also much greater than the S-20 photocathode, thus providing another three fold increase.

There are two configurations of the third generation tube currently in production. One configuration has a fiber optic inverter and a miniaturized power supply. This tube is used in the Aviator's Night Vision Imaging System (ANVIS). The objective lenses in this system are coated with a dielectric film (called a minus blue filter) that rejects wavelengths less than 600 nm. so the ANVIS is compatible with the blue-green crewstation lighting. The other third generation tube configuration has no fiber optic inverter and is used in the AN/PVS-7, One Tube Night Vision Goggles, and Cat Eyes.

The luminance output of the first, second, and third generation devices is determined by the amount of current the power supply will provide. The total current drawn by the display is limited; the light generated by this current can be concentrated in one spot or distributed over the entire screen. The values provided in this paper are for full screen illumination; half the screen would be twice as bright. Small areas can be much brighter than the full-display luminance quoted in the tube specifications.

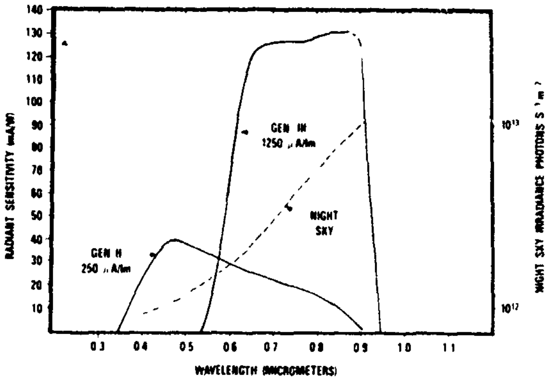

FIGURE 6. Comparison of sensitivities between second and third generation image intensifier tubes. Also shown is night sky irradiance.

Future Developments

Will there be a fourth generation? Probably not, is the answer image intensifier developers profess. There are, however, several improvements they would like to make on the third generation intensifiers. The third generation demagnification tube may be a low-cost, efficient image intensifier. For some applications, small size may not be a controlling factor, so the elimination of the expensive MCP and the enlargement of the photocathode may prove to be an alternative to present designs. Developers are also improving the photocathode manufacturing techniques and expect to make photocathodes with a luminous efficiency approaching 2,000 microamps/lumen in the near future.

FLIR, NVG and HMS/D systems for helicopter operation
Review

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SUMMARY

In the last decade, electro-optical systems have been used sucessfully in military and cicil applications. They extend the scope of operation of ground vehicles, helicopters and fixed wing aircraft from day-time into night-time, with a 24 hour readiness covering even bad weather conditions.

The visual aids fall into two physical categories: the image intensifiers, which amplify reflected residual light in the near infrared (approx. 0.6 - 0.9 µm) and the thermal imager (TI), which detect the thermal radiation of all bodies (Planck radiation) mainly in the 8-12 µm atmospheric window for bodies with $T \approx 20°C$.

The so-called Forward Looking Infrared (FLIR) is a thermal imager while Night Vision Goggles (NVG) belong to the image intensifiers which also includes Low Light Level TV cameras (LLLTV). The Helmet-Mounted Sight/ Display (HMS/D) has been specially developed to display information and to measure the Line of Sight (LOS) of the pilot's head in order to steer a sensor platform or a weapon without an additional workload. The display on the helmet (HMD) uses a mini Cathode Ray Tube (CRT) to produce a video image with superimposed symbology.

All of these images are produced by detecting the radiation in the near or far Infra-Red (IR) and transferring it to the visible range (0.4 - 0.7 µm) adapted for the human eye. The eye has to learn and interpret the information of this displayed monochromatic radiation, which is produced in the green sprectral range (0.5 µm) e.g. by CRT or a NVG phosphor screen and by LED in the red. These visual aids of both technologies guarantee the safety and efficiency of helicopter operation during night flights.

During the last five years, MBB has carried out helicopter flight trials at night using examples of all these visionic aids (FLIR, LLLTV, NVG, HMS/D and Direct View Optics (DVO) for piloting and observation tasks. The detection, recognition and identification ranges of nine different FLIR were tested in ground and laboratory tests. The evaluation of an optical sensor platform location in the helicopter nose-, roof- and mast-mounted versions, the comparison of thermal and intensifier images and the NVG compatible cockpit were topics of the tests. This paper describes in detail the optical sensors with their limitations and gives some results of the trials, with regard to the pilots stress situation and eye safety.

1. INTRODUCTION

Night vision systems extend our vision beyond the wavelength red (0.65 µm) into the near and far infrared (IR) by making this radiation visible. Because of the eye's lack of response in the absence of 0.4 to 0.7 µm light, devices are needed which will image the dominant energy at night as the eye does during the day. These electro-optical devices fall into two physical categories: the image intensifiers (NVG and LLLTV camera) which amplify reflected residual light in the near IR and the thermal imagers (FLIR), which detect the naturally emitted thermal radiation of bodies mainly in the far IR.

These electro-optical night eyes extend the scope of operation of ground vehicles, helicopters and fixed wing aircraft, for civil and military applications, from day-time into night-time with a 24 hour readiness covering even bad weather conditions. During the last five years, MBB has carried out helicopter flight trials at night using all of these visionic aids for piloting and observation tasks.

This paper describes first of all in Section 2 the visual perception of the human eye. The contrast, resolution, luminance, meteorological range, discrimination level of targets are some parameters of the visual perception. Section 3 covers EO-sensors as visual aids for round-the-clock operation. A short description of the physical sensor function and a comparison between the sensors is included. Section 4 presents the monitoring of sensor images with different displays. These night vision systems can be used for different applications as is shown in Section 5: "Helicopter vision systems as visual aids". The section is divided into two parts: pilot vision systems (PVS and PISA) and an observer visionics system (OPHÉLIA). The latter includes the advantages and disadvantages of a mast-mounted sight (MMS). This section describes shortly the integrated visionics systems and gives some of the trial results. Section 6 summarizes the conclusions.

2. VISUAL PERCEPTION OF THE HUMAN EYE

The human eye is the most highly developed visual system in existence. It has a moderate quality field of view (FOV) of approx. 30° in EL and 40° in AZ, a high quality circular field called the foveal field of about 9° and a best vision field of about 1° to 2° in diameter.

The 30°x40° field is used in most visual tasks and it is for this reason that most sensors operate with 3:4 aspect ratio fields (e.g. commercial television). Colour vision with cones extends over about 90° of the central field, with colour sensitivity decreasing as the retinal edge is approached. The very rim of the retina with rods does not produce a conscious sensation of vision and is used only for motion detection. A normal youthful eye can focus on objects as close as about 25 cm, but this minimum adaptation distance increases with age (ref. 1).

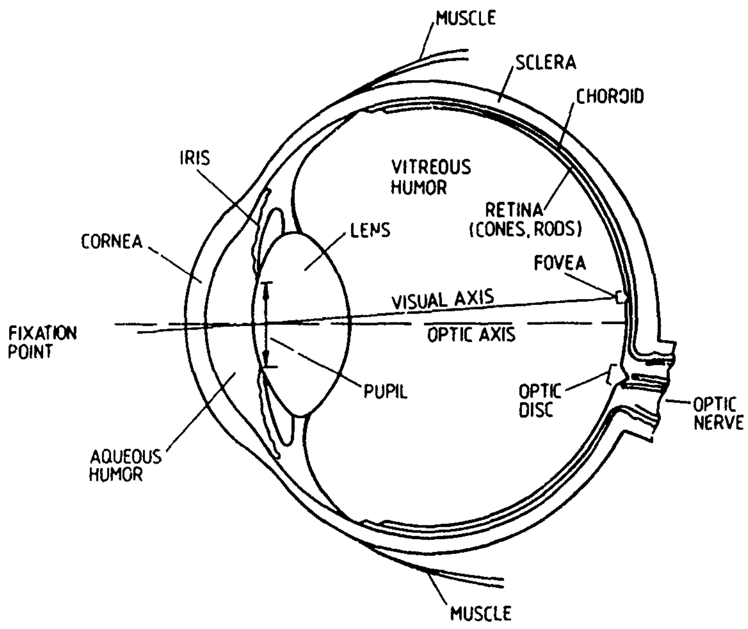


Fig. 1 Cross-section of the human eye. The cones for the colour and the rods for the black and white vision are located in the retina

The visible region lies between 0.4 µm (violet) and 0.7 µm (red) of the total electromagnetic radiation spectrum. The measurement in this region is called photometry. The human eye is able to detect this small spectral distribution with the cones and the rods in the retina (fig. 1). The sensitivity maximum of the cones is at a wavelength of 555 nm and of the rods at 507 nm (see fig. 6). The cones are located mainly in the fovea centralis with approx. 7 million cones with 4 µm diameter each. They are responsible for the colour vision. The rods of the retina are used for the black and white vision. They are located mainly at the rim of the retina. In the retina exist approx. 123 million rods with 2 µm diameter each.

The dynamic range of the eye related to the luminance is spread over 10 decades. This luminance range is divided into 3 regions (ref. 2):

- scotopic range (night: rods for black and white vision): 10^{-5} to 10^{-3} cd/m²
- mesopic range (twilight: rods and cones): 10^{-3} to 10 cd/m²
- photopic range (day: cones for colour vision): 10 to 10^{5} cd/m²

The quick adaptation of the eye to different luminance levels is achieved by the variable pupil diameters of 2.5 to 8.3 mm. The slow adaptation is achieved by switching or change-over processes in the retina.

The resolution capabilities of the eye can be described in several different ways. Perhaps the simplest measure of visual resolution is the visual acuity, the reciprocal of the smallest angular detail in milliradians resolvable by the eye. Visual acuity decreases as the position of the target moves away from the LOS. The geometric resolution of the eye is measured by the spatial frequency r (Lp/mrad). It is a function of the threshold contrast C (%), the luminance L (cd/m²), the pupil diameter D (mm) and the time of target exposure t (ms). The integration time of the eye is approx. 0.2 s. The contrast can be defined in two ways:

$$C = \frac{L_1 - L_2}{L_1} \quad \text{and} \quad K = \frac{L_1 - L_2}{L_1 + L_2} \tag{1}$$

L_1 is the target luminance and L_2 the background luminance in cd/m².

In 1948 Rose formulated (ref. 3) an equation of the detective quantum efficiency of an ideal image detecting system. The human eye is a real photon counter. The threshold contrast detectable by eye for the visible is proportional to:

$$C \cong \frac{r}{D\sqrt{L \cdot t}} \approx \frac{r}{\sqrt{L}} \qquad (2)$$

in the vicinity of the target. Measurements of the geometric eye resolution depending on contrast and different luminance levels are given in fig. 2 .

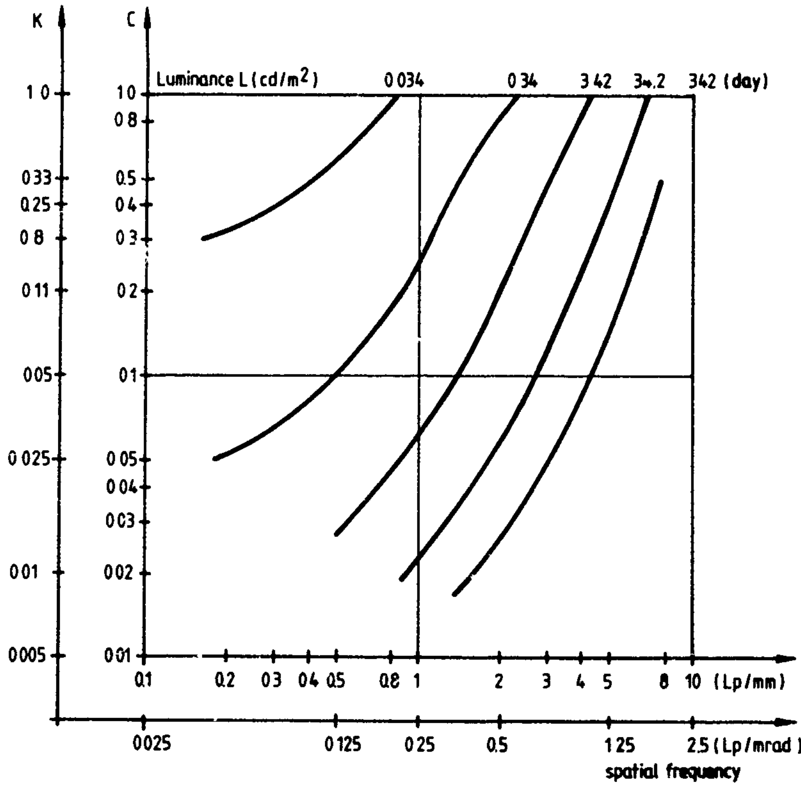


Fig. 2 The threshold contrast as function of the spatial frequency r for the human eye. The luminance L is the variable, see formula 1, 2 and 3 (from company Zeiss).

The relation between r´ (Lp/mm) and r (Lp/mrad) with the average focal length of the eye f_{eye} = 0.25 m is

$$r = r' \cdot f_{eye} = r' \cdot 0.25 \text{ m} \qquad (3)$$

The eye is not a linear spatial filter for small spatial frequencies (large targets) around 0.1 Lp/mrad. The curves have a point of inflections below this frequency and the contrast then increases with smaller spatial frequencies (ref. 4 and 5).

For large distances the atmospheric transmission τ_a is taken into account in the calculation. The mathematical models as functions of the wavelength λ incl. absorption lines etc. are very complicated. The Lambert-Beer law describes this process in a simple way:

$$\tau_a(\lambda) = e^{-\sigma(\lambda) \cdot R} \; [-]$$

$$C' = C \cdot e^{-\sigma \cdot R} \; [-] \qquad (4)$$

R (km) is the range and σ (km^{-1}) the extinction coefficient. In the visible spectrum the meteorological range V_N is defined. Koschmieder says that the eye can resolve 2% contrast. With this value, 100% contrast at the target and formula 4 it follows (ref. 6):

$$V_N(\sigma) = \frac{3{,}912}{\sigma} \text{ [km]} \qquad \text{for the visible.} \qquad (5)$$

The diffraction angle θ (disc) of the eye is approx. 0.3 mrad in good contrast and brightness conditions:

$$\theta = 1.22 \cdot \lambda / D \qquad \text{D is the pupil diameter} \qquad (6)$$

In 1958 J. Johnson found different target criteria N_x in the form of bar patterns from many measurements with image intensifiers (ref. 5 and 7). The classification of discrimination levels for the small target size is given in table 1. The S/N ratio and the contrast must be high. The perception probability of these values is 50%. The N_x for the MBB/Aerospatiale calculation is given additionally for 50% and 90%.

Classification of discrimination level	Meaning
Detection	An object is present
Orientation	The object is approximately symmetric or asymmetric and its orientation may be discerned
Recognition	The class to which the object belongs may be discerned (e.g., house, truck, man, etc.)
Identification	The target can be described to the limit of the observer's knowledge (e.g., motel, pickup truck, policeman, etc.)

Discrimination criteria	MBB/Aérospatiale		J.Johnson
Perception probability	50 %	90 %	50 %
Detection $\hat{=} R_{Det}$	1.0	1.8	$1.0^{+0.5}_{-0.25}$
Orientation $\hat{=} R_{Or}$	-	-	$1.4^{+0.4}_{-0.2}$
Recognition $\hat{=} R_{Rec}$	3.5	6.3	$4.0^{+0.8}_{-0.2}$
Identification $\hat{=} R_{Id}$	7.0	12.5	$6.4^{+1.6}_{-1.4}$

Table 1 Target discrimination criteria for the small target size. MBB-Aérospatiale and J. Johnson Model with 50% and 90% perception probability. N_x in line pairs.

Fig. 3 presents the Johnson idea of optical image transformation with bar patterns (line pairs) and examples for detection, recognition, identification together with a highly resolved tank.

The NATO target size is defined as 2.3 m x 2.3 m. If 7 line pairs or cycles are seen on the target this means identification of the target. The transformation from the spatial frequency r into the different ranges R_x is possible with the discrimination criteria N_x and the small target size h:

$$R_x\,[\mathrm{km}] = \frac{h\,[\mathrm{m}]}{N_x\,[\mathrm{Lp}]} \cdot r\,[\mathrm{Lp/mrad}] \cdot \theta\,[\mathrm{mrad}]$$

$$= \frac{2{,}3}{N_x} \cdot r \cdot \theta \qquad \text{for the NATO target} \qquad (7)$$

θ is the normalized angle in 1 mrad.

Fig. 4 shows the resolvable ranges of the unaided eye at day-time. The contrast at the target is 50% and the target size 2.3 m x 2.3 m. The calculated curves uses equ. 2, 4 and 7 and the discrimination criteria. The intersections of the different transmission curves with the threshold contrast curves of the eye (see fig. 2) gives the ranges.

Table 2 presents the recognition range (3.5 Lp / 2.3 m) for the unaided human eye.

3. ELECTRO-OPTICAL SENSORS AS VISUAL AIDS FOR ROUND-THE-CLOCK OPERATION

The relaxed adapted eye (30 min time for adaptation) can detect signals only in black and white up to 10^{-5} cd/m² luminance as described in section 2. The eye is then at its limit of capability.

Electro-optical sensors using night vision techniques can extend the scope of operation of ground vehicles, helicopters and fixed wing aircraft from day-time into night-time, with a 24 hours readiness covering bad weather conditions.
These visual aids fall into two physical categories:

- the image intensifiers, which amplify reflected residual light in the near infrared (0.6-0.9 µm) and
- the thermal imagers, which detect the thermal radiation of all bodies (Planck radiation) mainly in the 8 - 12 µm atmospheric window for bodies with $T \cong 20°C$.

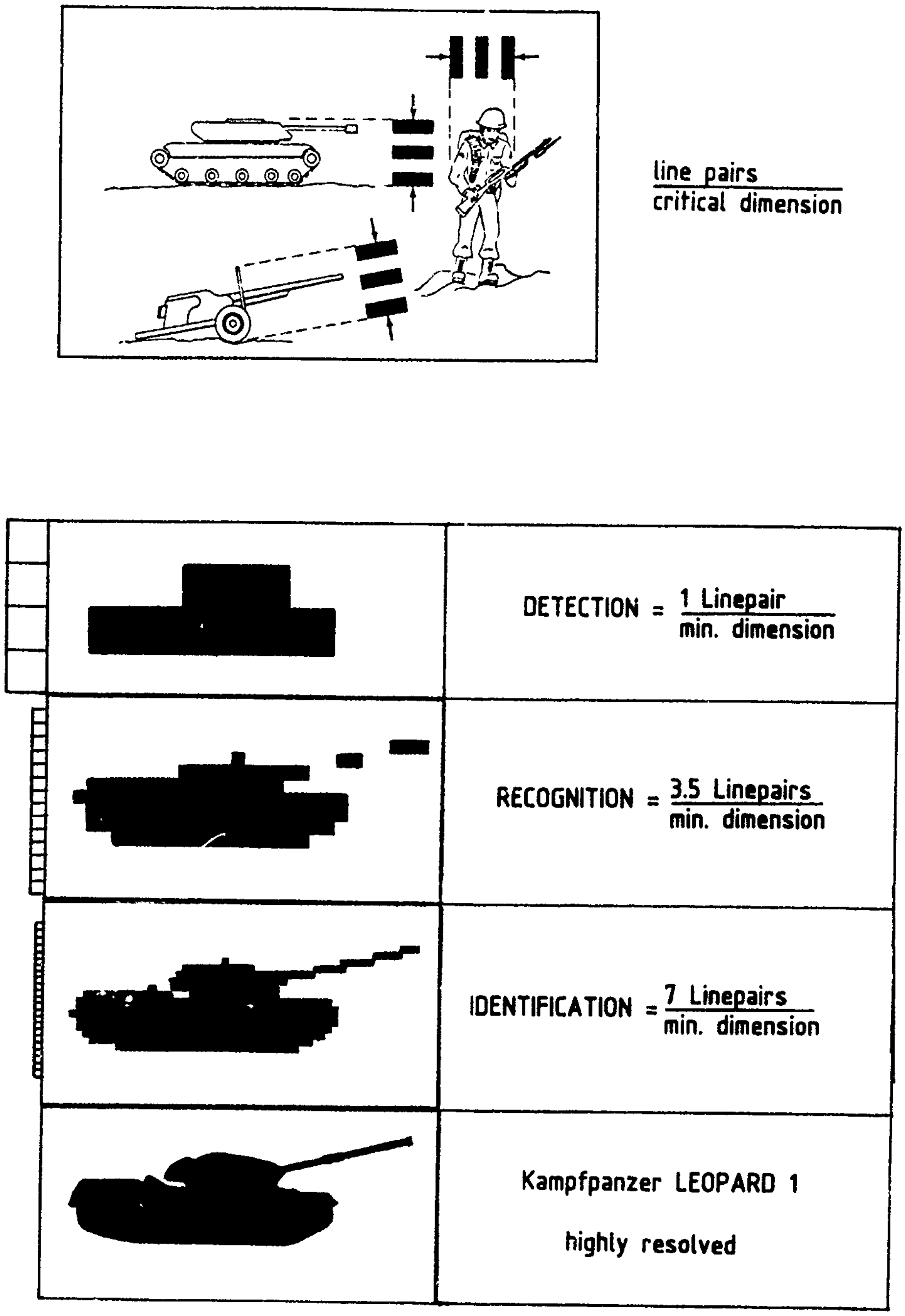


Fig. 3 Johnson method of optical image transformation above (refs. 5 and 7). Required resolution for detection, recognition and identification with a higly resolved tank, shown below

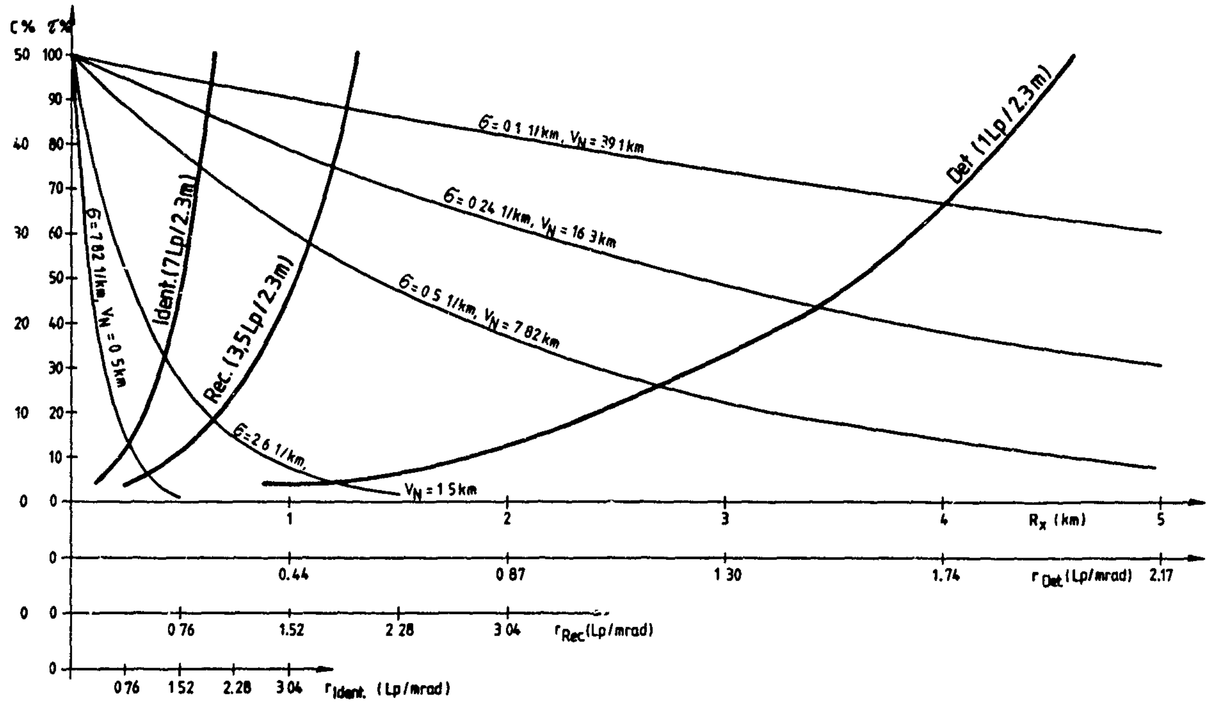


Fig. 4 Minimum resolvable threshold contrast (resolution of the eye) as function of the range and the spatial frequency for three different discrimination levels N_x of the unaided eye. The day luminance is ≙ 342 cd/m², the target size 2.3 m x 2.3 m with 50% contrast and 50% perception probability. Five transmission curves are added: σ = 0.1, 0.24, 0.5, 2.6 and 7.82. The intersections with the threshold contrast curves delivers the ranges. The corresponding resolvable spatial frequency of the human eye is shown on different scales.

Contrast at the target	σ = 0.24 1/km V_N = 16.3 km	σ = 0.32 1/km V_N = 12.2 km	σ = 0.5 1/km V_N = 7.8 km
100 %	1.5	1.4	1.25
60 %	1.3	1.25	1.1
30 %	1.05	1	0.85

Table 2 Visibility ranges (km) at day-time of the naked eye for recognition (3.5 Lp/ 2.3 m) with the variables contrast C and weather conditions σ or V_N.

3 a Image Intensifiers

The image intensifiers are used in Night Vision Goggles (NVG) and in Low Light Level TV cameras (LLLTV cameras).

The levels of obscurity for the night are shown in table 3. The visibility ranges are strongly dependent on the four seasons with different levels of the different moon phases and cloud conditions. Additionally, a high contrast between an obstacle and its background is necessary to obtain good detection range with image intensifiers.

1. LEVELS OF OBSCURITY (NIGHT)

LEVEL OF OBSCURITY	% PER YEAR	NIGHT	ILLUMINATION: MEASURED IN MILLILUX	ILLUMINATION: MOON + CLOUDS	AVERAGE VISIBILITY (good weather conditions) IN METRES: RECOGNISED SILHOUETTE: TANK FRONT VIEW	RECOGNISED SILHOUETTE: KNEELING MAN	VISIBILITY TRIANGLE: DETECTED	VISIBILITY TRIANGLE: RECOGNISED
a	b	c	d	e	f	g	h	i
1	14	VERY CLEAR						
			40		200	70	83	52
2	24	CLEAR		OR / OR				
			10		100	40	45	24
3	7	NORMAL		OR				
			2		25	17	28	16
4	27,5	DARK		OR				
			0,7				16	11
5	27,5	VERY DARK		OR				

LEGEND:

Column (e)
- Full moon
- Half-moon
- Waning moon
- New moon
- Slight or medium cloud cover
- Thick or very thick cloud cover

Column (b)
Average values, measured over a period of one year in southwest France, using an illumination meter of type SPECTRA PRITCHARD 1970 R.

Columns (h) and (i)
Visibility triangle:
a white equilateral triangle with sides of length 22,7 cm, silhouetted against a black square
Recognition achieved by varying orientation of the apex, S.

NOTE: At night, the presence of precipitation (rain or snow) mist or particularly fog reduces the quoted visibilities (columns (f), (g), (h) and (i)) for all levels of obscurity.

DEFINITIONS: VISIBILITY (by day or night) = for a given illumination, visibility decreases in the presence of suspended particles (fog, mist, rain and snow) particularly with increasing cloud cover
BAD OR LIMITED VISIBILITY = 5 levels of obscurity at night + daytime visibilities 1 & 2
OBSCURITY = Absence of light for the eye
GOOD WEAHTER = No fog, mist, precipitation by day or night
FOG = term for opacity
MIST = slight fog, not very dense, not totally opaque

Table 3 Distribution of the average illumination and levels of obscurity, from a Finabel Study

- Night Vision Goggles (NVG)

Unlike NVG used in troop operations on the ground, NVG used in helicopter operations have a different mechanical mounting. The NVG in the troop version are worn with a face mask and a harness. For helicopter applications, the electro-optical industries together with the Army pilots (ref. 8) have, in the last few years, developed helmet-mounted NVG. The reason for this development is that the pilot can look around the goggles into the cockpit and onto the instrument panels in front of him with his "naked eye". He sees through the goggles into the outside world (fig. 5).

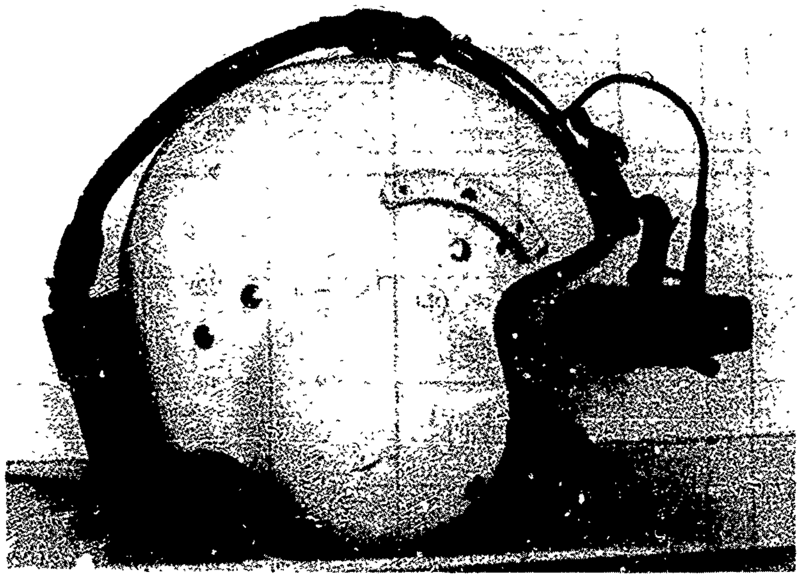


Fig. 5 Helmet-mounted NVG from Elektro-Spezial (type BM 8043 with 2nd plus gen. tubes) on the SPH 4 helmet with spotlight, lip-switch and fixed focus, (ref. 2).

The human eye is twilight adapted when using NVG. The image intensifier tubes produce a luminance of approx. 5 cd/m² on the phosphor screen (P20). With the use of the above mentioned helmet-mounted NVG it is not necessary to change the focus. The NVG can have a fixed focus with a depth of field of approx. 12 m to infinity. Because of two intensifier tubes in one NVG, it is possible to have a binocular view of the outside world. The evaluation of obstacle ranges is possible.

The basic purpose of NVG is to extend the possibility of vision towards lower light levels through high resolution in the near infrared spectrum. Fig. 6 contains four diagrams of interest when considering image intensifier tubes. The wavelength range from the visible to the near infrared (0.3 - 1.1 µm) is shown in all four diagrams.

The first diagram contains the relative photocathode sensitivity for 2nd and 3rd generation tubes; the second diagram describes the relative night sky irradiance of starlight, vegetation and cloth reflections and, on a different scale, moonlight, reflected light of the sun. Black body radiation is not shown. The relative day and night sensitivity of the human eye (photopic and scotopic response curve) is shown in the third diagram. The last diagram contains the relative luminance of two electro-luminescent (EL) illuminations with blue and green colour and the transmission of a dyed-glass filter (BG 7) and a cut-off filter (OG 590). Annex 1 presents radiometric and photopic units.

There exists a large difference in the spectral sensitivity between the 2nd and 3rd generation tubes (see fig. 6, diagram 1). The major difference between the 2nd generation and 3rd generation tubes (fig. 7) is the photocathode. The infrared sensitive photocathode of the 2nd generation is referred to as red extended alkali antimonide e.g. S 20 or S 25. Single-stage wafer or inverter tubes are used. They are also sensitive in the visible region.

The 3rd generation photocathode uses the semi-conductor single crystal material GaAs/GaAlAs as epitaxial structure. The probability of the photoelectrons reaching the sureface is proportional to their diffusion length, which can be over 5 µm. The spectral sensitivity has a range between 0.55 and 0.90 µm, and is very different to that of the 2nd generation.

With the 3rd generation tube it is possible to better amplify ambient light from the night sky (see fig. 6, diagram II). The 3rd generation tubes use only a high performance wafer tube.

Both generation tubes use microchannel plates (MCP) with a high current gain. They are able to reproduce a two dimensional electronic image with high resolution. In all tubes the 18 mm diameter image intensifiers are in fact a set of 1.3 million circuits: detector-amplifier-display. The diameter of one microchannel is between 10 and 20 µm. With the MCP it is possible to control the brightness and gain of the NVG. The well-known blooming

effect is now a secondary problem, since the individual microchannels saturate.

The main idea of the NVG compatible cockpit design is that the lighting should not interfere with the spectral sensitivity of 2nd and 3rd generation tubes. Therefore blue, green illumination for the cockpit and exterior lighting should be used (ref. 2). Fig. 8 shows a view through the NVG into the outside world.

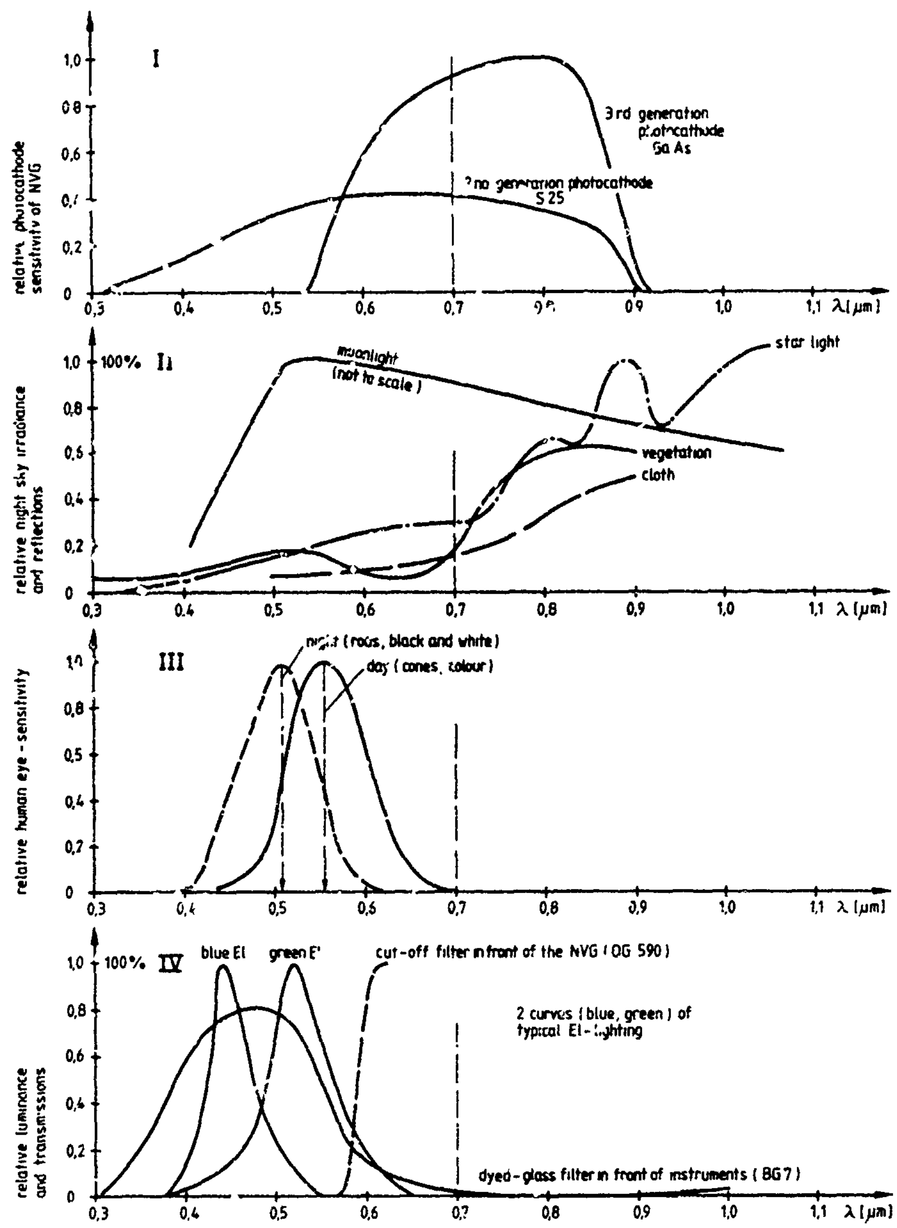


Fig. 6 Various image intensifier (NVG) parameters as function of the wavelength (ref. 2)

- Low Light Level TV Camera (LLLTV Camera)

A variety of LLLTV systems are available, ranging from simple devices consisting of a fibre-optic coupled combination of TV camera tube and image intensifier (intensified Vidicon) to more complex systems in which the intensifier and Vidicon are an integral unit contained within the same vacuum envelope.

These so-called intensified-silicon Vidicons (ISV) include a special target (Silicon Intensified Target) which is responsive to electrons. In SIT devices the image intensifier phosphor screen is omitted, allowing the photoelectrons to impinge directly on the target (see fig. 9). SIT tubes (NATO approved name: EBSICON) are suitable for use with moonlight illumination. For starlight conditions, intensifier EBSICONS are available, which have a further intensification stage. The spectral sensitivity range of the LLLTV image intensifier is similar to the NVG tubes described in fig. 6, diagram I.

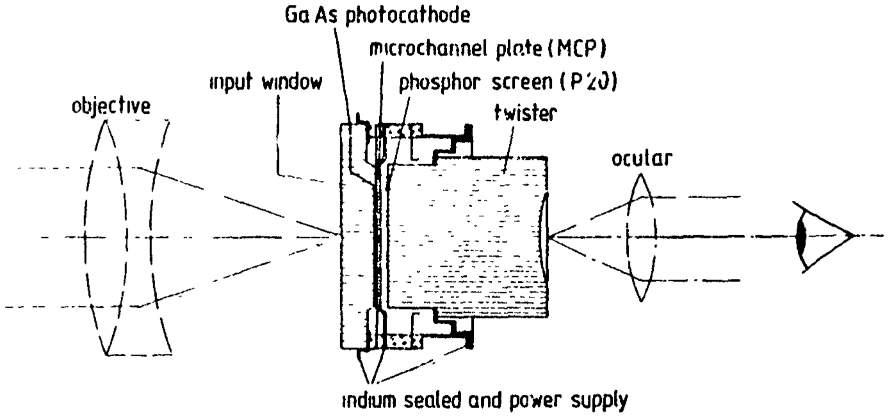


Fig. 7 3rd generation tube design of wafer (proximity) type with a micro-channel plate and integrated twister (fibre optic) (ref. 2)

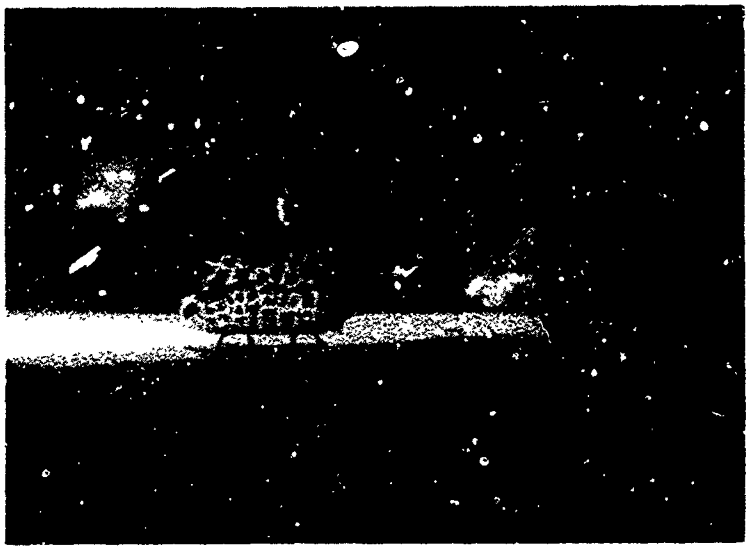


Fig. 8 View through NVG with 3rd gen. tubes. Blooming effects are insignificant because of MCP saturation (ref. 19)

For helicopter applications, LLLTV systems can be remotely mounted and controlled e.g. on external sensor platform, and the images relayed to the pilot by means of a coupled display. Fig. 10 and 18 are reproductions from LLLTV video recordings

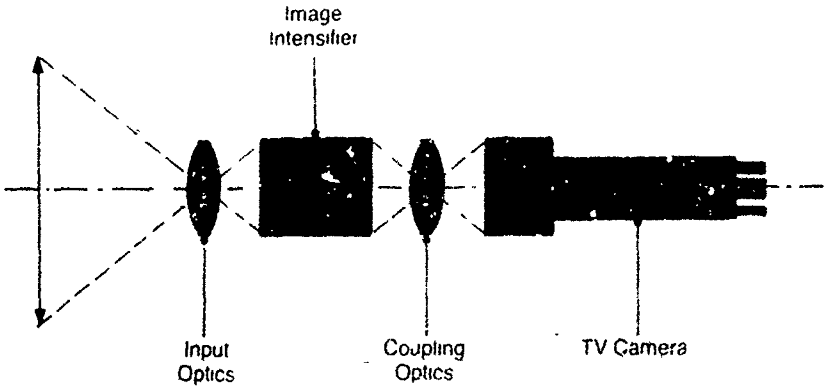


Fig. 9 Schematic drawing of a LLLTV camera (ref. 22)

3 b Thermal Imager (TI, FLIR)

First the physical aspects of thermal radiation are described. All objects having a temperature greater than absolute zero (-273°C or 0 K) emit electromagnetic radiation over a continuous range, of wavelength from the radar region to the infrared region to the visible region (with 1000 K and more in the latter). The amount of energy emitted depends

On both the object's temperature and its surface condition, or emissivity, and is independant of ambient light.

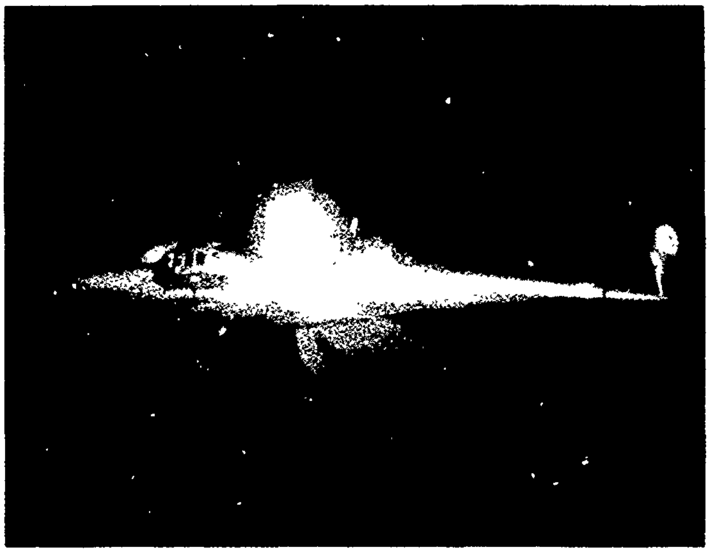


Fig. 10 Reproduction from a LLLTV video recording

In 1900 Planck's Law was defined for the spectral radiant emittance M_λ of a black body

$$M_\lambda(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \left(e^{hc/\lambda kT} - 1\right)^{-1} = L_\lambda \cdot \pi \quad \left[\frac{W}{cm^2\,\mu m}\right] \qquad (8)$$

$c = 3 \cdot 10^{10}$ cm/s speed of light in vacuum; $h = 6.626 \cdot 10^{-34}$ Ws² Planck's constant; $k = 1.38 \cdot 10^{-23}$ Ws/K Boltzmann's constant; λ = wavelength; T = temperature and L_λ the spectral radiant steerance. For any given object, at a given temperature, there is only one wavelength where the energy is at a maximum. Wien's displacement law describes the wavelength maximum λ_{max}

$$\lambda_{max} \cdot T = 2898 \ [\mu m \cdot K] \qquad (9)$$

Integration of Planck's law yields the Stefan-Boltzmann law. The total radiant emittance M(T) is

$$M(T) = \sigma \cdot T^4 \ [W/cm^2] \qquad (10)$$

$$\sigma = 5{,}6686 \cdot 10^{-12} \ [W \cdot cm^{-2} \cdot K^{-4}] \quad \text{Stefan-Boltzmann-Constant}$$

In fig. 11, diagram 1, the black body radiations for different temperature (Planck's Law) are given, (ref. 2, 9 and 10). The emitted radiation must travel from the object to the observer through the atmosphere, which itself absorbs energy of the radiation.

Fig. 11, diagram 2, describes the atmospheric transmission in the region of 0.3 µm to 14 µm. There are a number of narrow bands or "windows", two of which are in the infrared 3-5 µm and 8-14 µm spectral bands. The shorter wavelength corresponds to higher temperature objects and transmission here is limited by smoke and haze. Energy at the longer wavelengths corresponds to radiation from objects at ambient temperatures e.g. human beings, natural vegetation around 300 K. It has a greater atmospheric penetration than the visible radiation.

The spectral range of optical materials for the telescope coating, Ge or ZnSe for the 8-14 µm range, is also presented in fig. 11, diagram 3. In order to detect the infrared energy present, photosensitive semi-conductor elements e.g. HgCdTe are mounted in an array at the focal plane of the telescope. The array may consist of one or more detectors arranged in one of six possible array patterns (ref. 11, 12, 13 and 14):

- single	
- parallel	e.g. US-Common Modules (CM)
- serial	e.g. Mini-FLIR Detector array
- serial-parallel	e.g. SMT, IRCCD
- quasi-serial-parallel	e.g. SPRITE
- focal plane arrays	under development

The most prevalent detector used for FLIR's is mercury cadmium telluride, HgCdTe, with a broadband spectral response peaking between 10 and 12 µm (see fig. 11, diagram 4). A photodetector which exhibits performance at theoretical limits is said to operate in the background-limited photodetection (BLIP) mode. Two different applications of the detectors are possible, photoconductive, PC, as used by US-CM and photovoltaic, PV, as used by IRCCD.

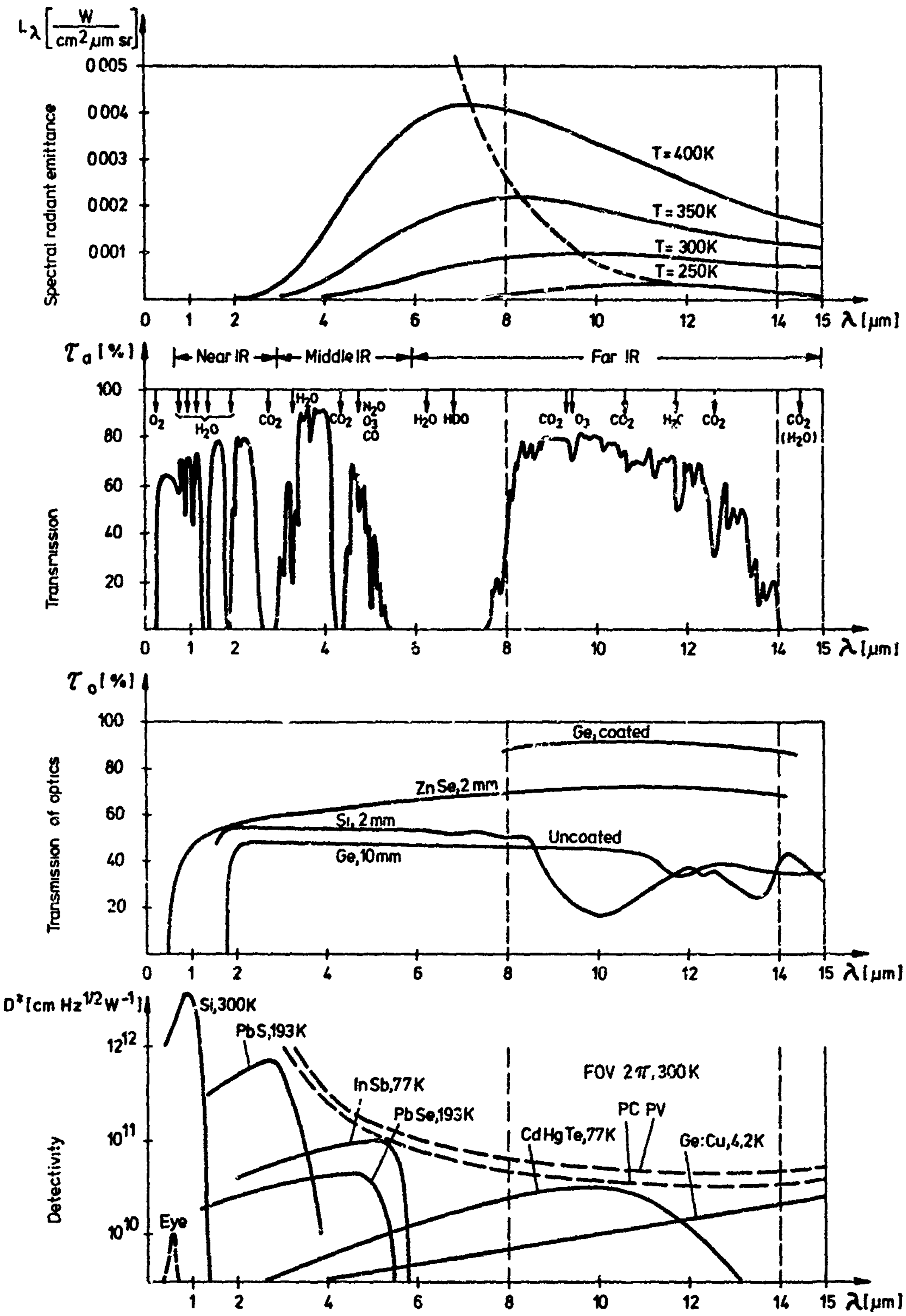


Fig. 11 Various TI parameters as functions of the wavelength λ (ref.10)

a) black body radiation for different temperatures (Planck's Law)
b) atmospheric transmission
c) IR optics transmission
d) IR detector detectivity with BLIP conditions for PV and PC

To ensure the satisfactory functioning of the detectors, the array has to be cooled to very low temperatures. In the case of HgCdTe detectors, the operating temperature is 77 K. Cooling is achieved by means of either an open cycle using liquid nitrogen, Joule Thomson principle, or a closed cycle miniature cooler.

A schematic setup of the thermal imager components: telescope, scanner, detectors with cooling unit, signal processing unit, display with the eye/brain response and the IR radiation with the atmospheric transmission is given in fig. 12. Thermal imagers mainly utilize the 8-14 µm window.

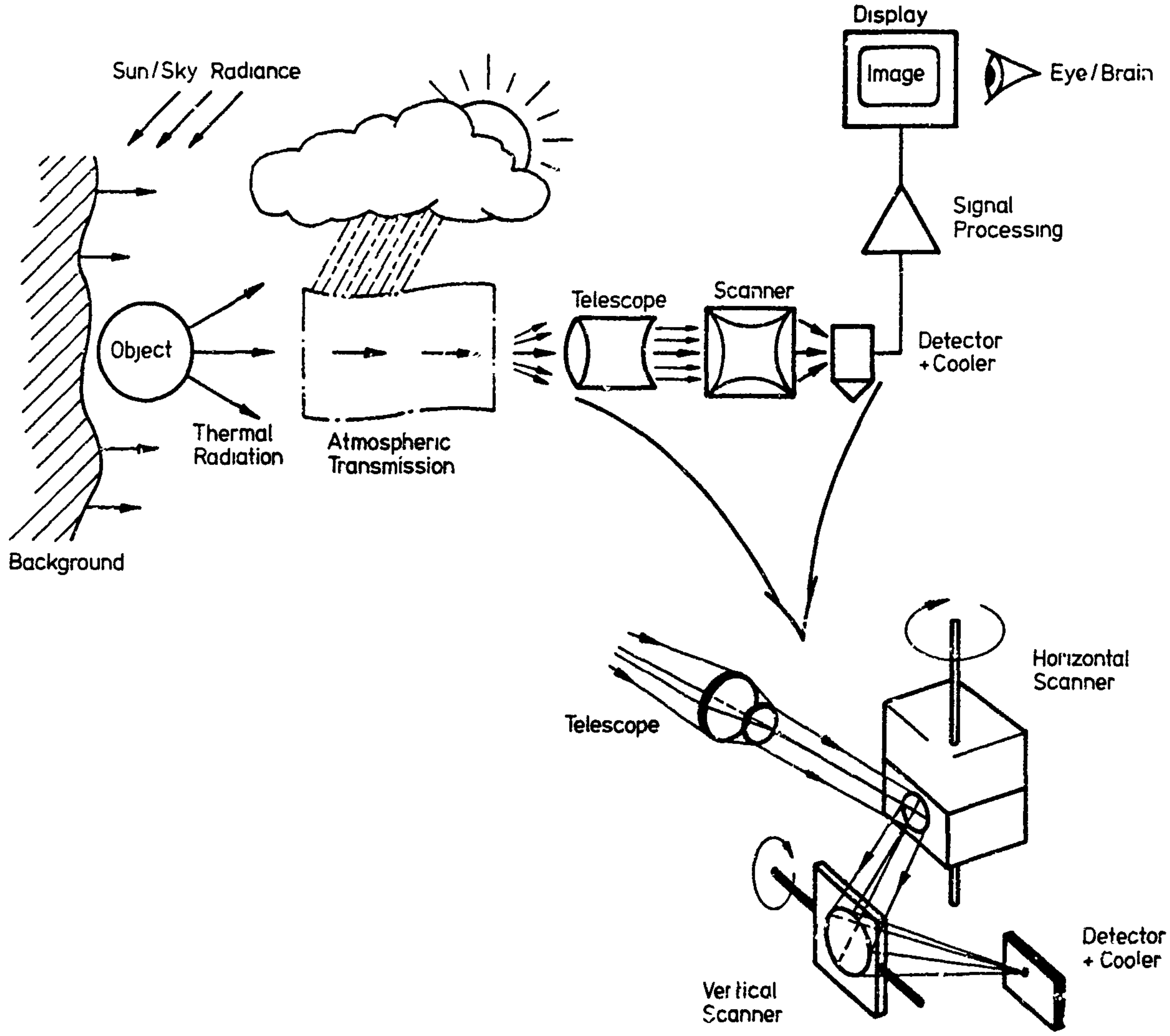


Fig. 12 Schematic set-up of the thermal imager components and the IR radiation with the atmospheric transmission

To produce a visible image of the thermal radiation in the IR, the TI detects the temperature difference ΔT of a scene. Therefore, the temperature derivation of equation 8 is detected by a thermal imager. Each detector converts the radiation into an electrical signal. In most cases, the signal processing unit produces a video signal for the display unit. The total temperature contrast K_T or radiation contrast of two black bodies for the total spectral range is defined with temperatures:

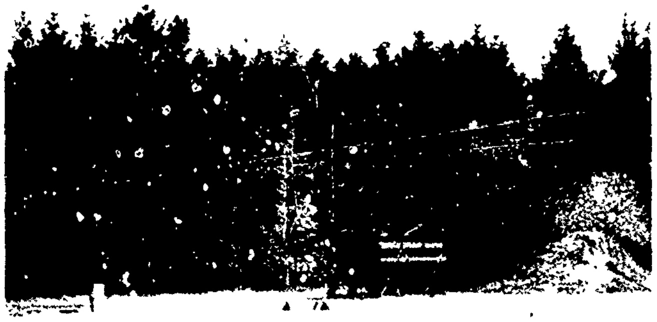
$$K_T = \frac{T_O^4 - T_B^4}{T_O^4 + T_B^4} = \frac{M_O - M_B}{M_O + M_B} \quad [-] \tag{11}$$

T_O (K) = object temperature, T_B = background temperature and M (W/cm²) is the total radiant emittance.

In a TI, the mechanical scanning to produce a thermal image is carried out in either one or two dimensions, depending on the described type of array pattern used (see fig. 12 below). TI's can be either direct or indirect view systems. In the former, detector elements are connected directly to light-emitting diodes (LED) viewed through an eye piece whose responses are proportional to the detected IR radiation levels. An indirect view system converts each detector output into an electrical signal, which then drives a conventional monitor raster scan.

Most countries involved in thermal imaging have developed TI systems configured from

so-called Common Modules (CM) or basic building blocks. These modules are designed to be arranged and located as required, providing the user with a flexible and ultimately lower cost system (ref. 11 and 12).



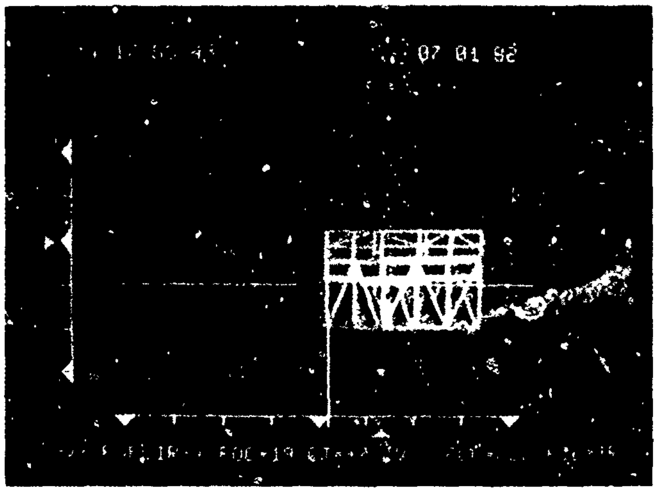


Fig. 13 Normal picture taken with photographic apparatus (above) and thermal image taken with CALIPSO-FLIR (below)
The information provided of the same scene is different (ref. 9)

The information of a thermal image is quite different from an image taken by a photo camera, see fig. 13. A user e.g. a pilot or an observer, has to learn and interpret the informations on a thermal image. The contrast of this image consists of temperature differences in the spectral range of 8-12 µm (see equ. 11 for the total spectral range) or emission factor differences. In a normal mode, hot bodies are white and cold bodies are black. The gain and the brightness levels of a TI are partly responsible for the image quality. A so-called polarity change of the thermal image can produce an image more similar to the visible range, e.g. snow is then looking white.

The thermal and geometric resoution of a TI are calculable using a model, with the minimum resolvable temperature difference (MRT) formula as function of the spatial frequency r (Lp/mrad), ref. 1, 9, 15 and 16.

$$MRT(r) = 0.756 \cdot \frac{U_s}{U_r} \cdot \frac{NET}{MTF(r)_{syst}} \cdot \sqrt{\frac{1}{t_e \cdot F \cdot \eta}} \cdot r \cdot \frac{\alpha_D}{\sqrt[4]{1 + 4r^2 \cdot \alpha_D^2}} \quad \text{(K or °C)} \qquad (12)$$

taking into account the parameters:

- U_s/U_r signal to noise ratio; 2,25 with 50% probability and 4.5 with 90% probability
- NET noise equivalent temperature difference in °C or K
- MTF_{syst} system modulation transfer function
- t_e eye integration time; approx. 0.2 sec
- F frame rate of the image in Hz
- η degree of line overlap
- α_D detector angular subtense of a detector element or instantaneous field of view (IFOV) in mrad

The system MTF taking into account the optics MTF, the detector geometry MTF, the detector time dependence MTF, the scanner or stabilization MTF, the electronics MTF incl. signal processing MTF (the sampling function should be displayed without alising effects, Nyquist-Theorem), the display MTF and the eye MTF. A MTF_{syst} for vertical and horizontal bar pattern has to distinguish in the MRT formular 12, see ref. 16.

The NET is the black body target-to-background temperature difference measured in a standard test pattern which produces a peak-signal to rms-noise ratio of one at the output of a reference electronic filter when the system views the test pattern.

$$NET = \frac{2}{\sqrt{\pi} \cdot h \cdot c} \cdot (f/D)^2 \cdot \frac{\lambda_p}{\tau_o \cdot D^* \cdot \Phi} \cdot \sqrt{\frac{N \cdot F}{A_D \cdot n_s \cdot n_p \cdot \rho}} \quad (K \text{ or } °C) \tag{13}$$

- h Planck's constant: $6.626 \cdot 10^{-34}$ Ws²
- c speed of light in vacuum: $3 \cdot 10^{10}$ cm/s
- f optics focal length in cm
- D optics diameter (entrance pupil) in cm
- λ_p upper cut-off wavelength in cm
- τ_o optics transmission
- D^* detector sensitivity in $cmHz^{1/2}W^{-1}$
- Φ derivation of photon density according to temperature in photon/cm²sec K: approx. $3.2 \cdot 10^{15}$ photons/cm²sec K at 20°C
- N line numbers times pixels per line = numbers of pixels per image frame
- F frame rate in Hz
- A_D detector area in cm²
- n_s number of detectors in series
- n_p number of parallel detectors
- ρ scanning efficiency

The signal transfer function (SiTF) measured in cd/m²/K or the dynamic range of a TI describes the conversion from the temperature difference (ΔT) into the photopic luminance detectable by the eye (ref. 1). The gain of this conversion is controlled partly by the contrast control of the TI video monitor and an arbitrary DC level is added by the brightness control. The same classification of discrimination levels (see table 1) are used for the thermal imager models. Normally a perception probability of 50% is used. With equ. 7, the different ranges can be calculated.

The performance of a TI should cover the max. range of the weapons used. It is easy to understand that the relationship between resolution or range and FOV size should be optimized. If the FOV of the TI is too small, providing greater range or higher spatial frequency, the observer may not be able to detect or recognize a target, because of the long search process.

A high resolution TI for a helicopter should have a minimum of three FOV i.e. WFOV for detection, MFOV for detection and recognition and NFOV for recognition and identification, see figure 14. A 4th FOV with approx. 1° may be useful for identification, but this NFOV is not good for tracking and aiming. A gunner's TI has the same high requirement for thermal resolution as a pilot's TI, i.e. NET $\leq$ 0.05 K. This high resolution is necessary as enemy tanks or helicopters in future will have IR suppression to aid camouflage. Hot spots with cue identification will then no longer be possible and only visual identification will be practicable.

During the last 5 years, using a 0.35 m Ø and f= 1.8 m collimator, MBB has tested 9 different MRT's of TI (ref. 9 and 23):

- CALIPSO (SMT) from TRT, fig. 13 and fig. 23
- TICM (brit. CM, SPRITE) from GEC/ Rank, Taylor, Hobson
- IR 18 Mk II (SPRITE) from Barr & Stroud, figure 18
- PISA (SPRITE) from EGO/MBB, figure 20
- MIRA (serial-parallel) from MBB/Siemens/TRT
- WBG X (US-CM) from Zeiss
- Modell 2000A from FLIR Systems, figure 25
- IRTV 445 from Inframetrics
- Mini-FLIR (serial) from Honeywell

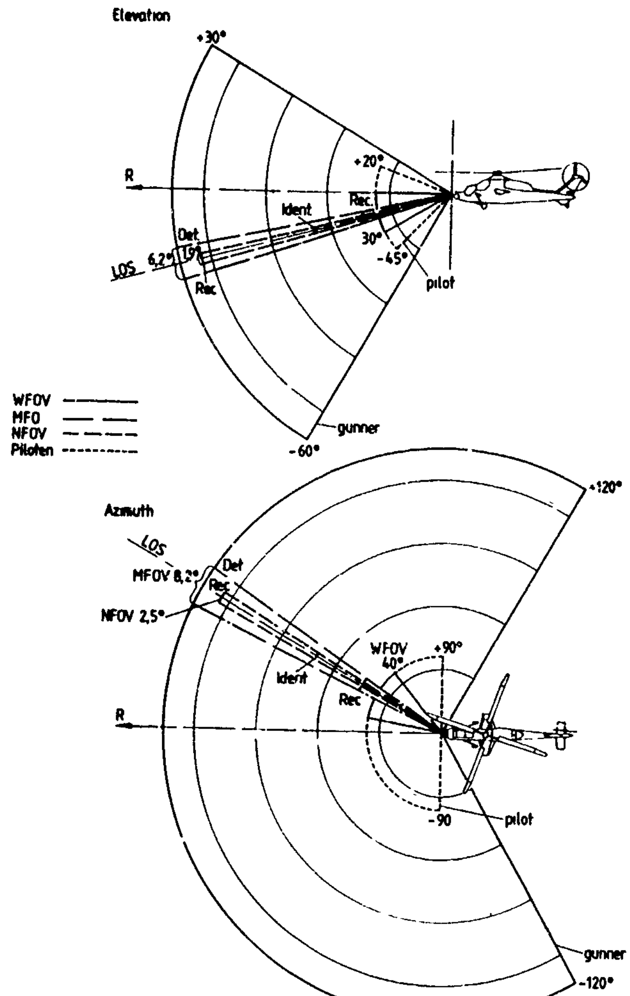


Fig. 14 FOV of a gunner TI on a stabilized platform in a nose-mounted sight (NMS) version

3 c EO-Sensor comparison

		ADVANTAGES	DISADVANTAGES
Image-Intensifiers	NVG	o direct view system o stereoscopic vision o easy to use o lightweight o natural image o low cost	o "blooming effects can be disturbing to the pilot o at present no possibility of superimposing flight data o minimum illumination necessary (Gen.II > 2 mlux, Gen,III > 0.5 mlux o instrument/cockpit lighting must be compatible
	LLLTV	o no system cooling required o no problems with thermal "crossover" o superimposition of flight data possible	o at present strong "blooming" effects o mimimum level of illumination (at present ≥ 5mlux) o indirect view system i.e. display required
	TI	o no "blooming o no low illumination limit o superimposition of flight data possible o in some cases better atmospheric penetration e.g. in fog, haze, artifical haze	o detector cooling required o images may lack natural perspective o indirect view system o thermal crossover- may give rise to obstacles "disappearing" for a time in the image

Table 4 A comparison of the three night vision sensors described as visual aids in the form of advantages and disadvantages (ref. 22)

4. MONITORING OF SENSOR IMAGES ON HMD, HDD (MFD), HUD AND EYE PIECES WITH CRT

The direct view system with LED's and eye pieces are not considered here (see section 3b). There are different possibilities for displaying the electro-optical images to the eyes, e.g. in a helicopter cockpit. One system is a helmet-mounted display (HMD) in front of the pilot's eye (fig. 17). In many cases the projection is monocular, with a beamsplitter to simultaneously see the video image and look into the outside world. In most cases, a cathode ray tube (CRT) is used to generate a video image. The CRT is located on the helmet or in the cockpit rear. In this case, the connection to the eye can be solved by means of a fiber-optic cable (approx. 0.5-1 Mill. pixels, high resolution).

For piloting tasks flying Nap of the Earth (NOE), the static FOV should be as large as possible to detect obstacles e.g. power lines. At the moment a 30°x40° FOV is possible with HMD in a 1:1 magnification. The LHX program desires a 60°x110° FOV to compare with the FOV of the human eye. But inevitable compromises have had to be made between resolution (EO-sensors and displays), FOV, luminance, amount of detail and cost. HMD with FOV bigger than 30°x40° in an 1:1 displayed scale, now use diffraction optics instead of the classical optics. An American with a Canadian company has a 64°x135° binocular FOV in development with two so-called Pancake Windows of 80° diameter each (ref. 17).

The problem of an extremely WFOV is the resolution and distortion of a TI. Equation 6 is also applicable. The wavelength λ in the 10 μm range is approx. 20x bigger than in the visible. This is also true for the resolution disc, if the entrance pupil has the same size as the eye. The F-number (f/D) of a TI should not be greater than 2-4. Protective filters against laser range finders (LRF) or low power laser weapons can be integrated in an HMD.

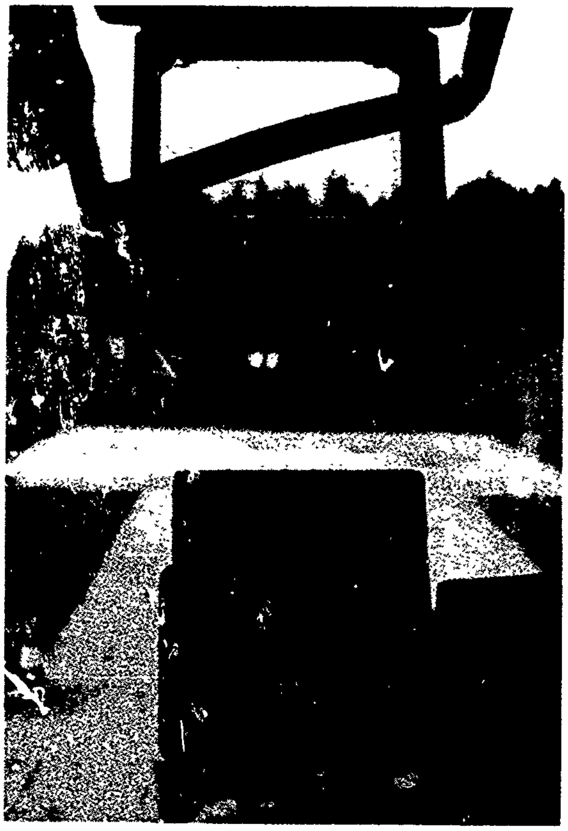


Fig. 15 HUD and HDD installed in the BO 105 helicopter during flight trials with the mast-mounted observation platform OPHELIA

A head-down display (HDD) for helicopter operation is normally installed in the instrument panel with a size of approx. 6"-8" diagonal, see fig. 15. The monitoring of WFOV image from an eye position of 70 cm distance is not in the scale 1:1. In some cases, the HDD, in the form of a coloured multi-function display (MFD), is used for flight guidance, flight management and/or navigation tasks, see fig. 20. A superimposed flight symbology with a symbol generator (SG) is state of the art.

The generation of weapon symbologies superimposed on sensor images on a head-up display (HUD) is sometimes desired in combination with a gun turret and rockets equipped on helicopters.

A gunner needs an eye piece with a high resolution CRT of approx. 50 mm Ø with a pixel size ≤ 30 μm for reconnaissance and combat assignments in order to resolve small targets at long distances. The display MTF must be adapted to the total MTF chain from optics of the sensor to the eye including the brain response.

A new STANAG document No. 3350, Issue 2 has been developed for airborne video applications, (ref. 18). The new video standards are called:

Class A: 875 lines, 60 Hz frame rate, ≤ 20 MHz bandwidth
Class B: 625 lines, 50 Hz frame rate, ≤ 15 MHz bandwidth
Class C: 525 lines, 60 Hz frame rate, ≤ 12 MHz bandwidth

Class A includes the high resolution EIA (American video standard) and Class B the CCIR (European video standard).

5. HELICOPTER VISION SYSTEMS AS VISUAL AIDS

Since 1981 MBB has tested different night vision systems on the BO 105 flying laboratory in order to evaluate specifications and to gain experience of such equipment for future developments.

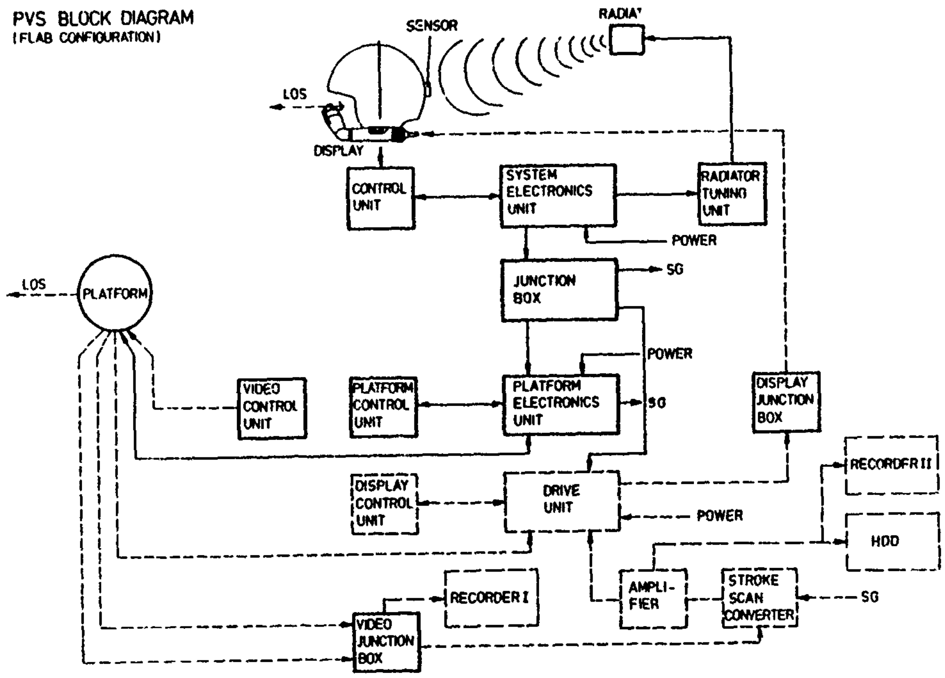


Fig. 16 Block diagram of the HMS/D with the platform as used in the PVS

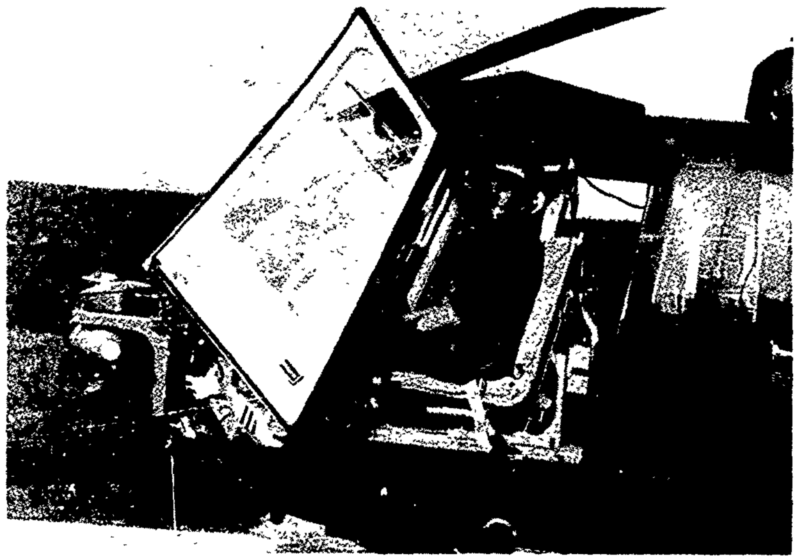


Fig. 17 Pilot with an HMS/D in conjunction with a visually-coupled platform which includes two EO-sensors (ref. 19)

5 a Pilot Vision Systems

Two pilot vision systems were mounted in the helicopter nose, ref. 19.

- PVS

The first was called Pilot Visionics System (PVS). The PVS comprises a Helmet-Mounted Sight and Display (HMS/D) with electromagnetic head position measurement, a stabilized steerable platform (AZ ±90° and EL +15°/-50°) with two electro-optical sensors, a TI (26° x 38°) with 4 SPRITE detectors and a LLLTV camera (30° x 40°). The LOS of the platform follows exactly the pilot's head movements by means of the measurement system (fig. 16 and 17). Images of the outside world are relayed to the pilot from the sensors and are displayed on a miniature CRT fitted to his helmet (HMD). For comparison purposes, a HDD was installed in front of the pilot. The sensor images on the displays could be superimposed with two different computer generated symbologies: Cruise and Transition/Hover.

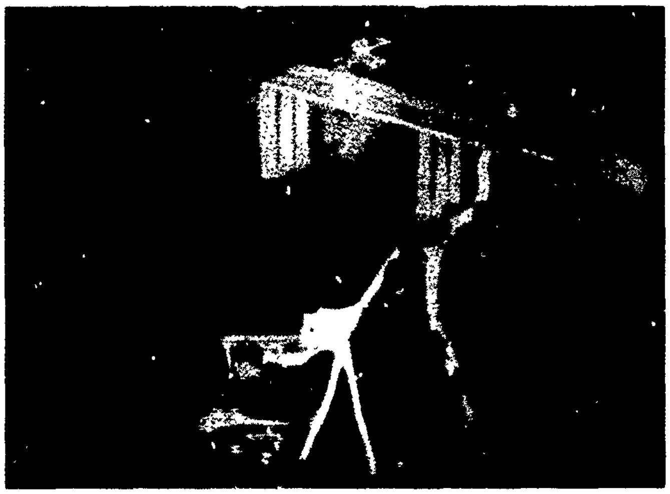


Fig. 18 Direct comparision of LLLTV (above) and TI (below) images during the same PVS night flight (approx. 200 mLux).
The images show a motorway bridge (ref. 19)

Additional tests were conducted to compare NVG with the electro-optical sensors of the PVS. 46 flight tests were performed, including 14 night flights. The TI and the LLLTV images could be displayed alternately to allow for direct comparison during the flight tests (fig. 18). The images were additionally recorded on video-tape. For post-flight evaluation a magnetic tape recorder was fitted to register 12 signals from the helmet, the controller and the platform, together with helicopter motion and the external illumination levels.

In addition to MBB, five companies from Germany, France and Great Britain participated in the project. The companies involved were Ferranti for the HMS/D; SFIM for the stabilized platform; Leitz who are licenced to produce the Barr & Stroud IR 18 Mark II infrared camera; AEG-Telefunken for the LLLTV camera and VDO for the HDD and the symbol generator (SG).

The HMS/D fulfils a dual function, firstly by determining the head motion of the crew member and secondly by displaying a sensor image directly in front of one eye. The HMS uses a three-axis electro-magnetic sensor mounted on the pilot's helmet. The radiator emits a magnetic field which induces voltages in the sensor. The sensor signals are then processed by the electronics unit to determine the position and attitude of the sensor relative to the radiator. Fig. 17 shows the HMS/D in conjunction with the steerable platform. Between the HMS and the platform lies a controller which relays the HMS signals to the platform. The optical sensor LOS follows exactly the pilot head movements.

- PISA

A simpler pilot vision system is demonstrated by PISA (Piloten Infrarot Sichtanlage). A beeper and a reset switch mounted on the collective stick were used for platform steering in AZ and EL. The platform contained a wide angle TI (30° x 60°) with 8 SPRITE detectors whose image was displayed on a large-screen HDD installed in front of the pilot. A new Cruise symbology could be superimposed on the image (fig. 20). 18 flight tests including 4 night flights were conducted with PISA.

The companies involved in the project were EGO for the TI, MBB for the platform, Koyo for the 12" black and white HDD and VDO for the SG. The new Cruise symbology was developed by MBB together with VDO.

Fig. 19 shows the nose-mounted platform, PISA, with the wideangle TI which contains 8 SPRITE detectors. The cockpit with a HDD was screened off for simulated night flights.

The tests showed that the platform displacement angles chosen (AZ ± 90° and EL +20°/ -45°) were very good, especially in combination with the FOV of the TI. The manual steering of the platform by means of a beeper switch on the collective stick needs a great deal of experience in order to coordinate the platform AZ and EL movements. Simple flight manoeuvres are possible with PISA but terrain following and NOE flights are not possible without excessively increased pilot workload. In this case, a HMS coupled system or NVG are much easier to use.

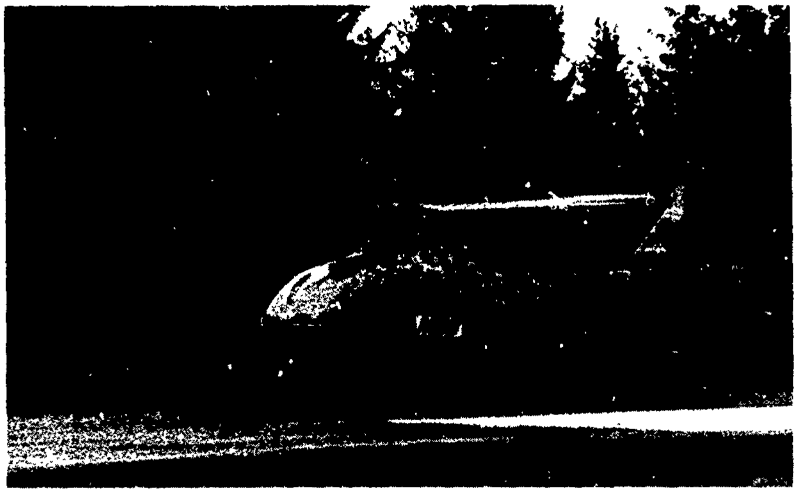


Fig. 19 BO 105 with the nose-mounted piloting platform PISA which includes a 30° x 60° TI

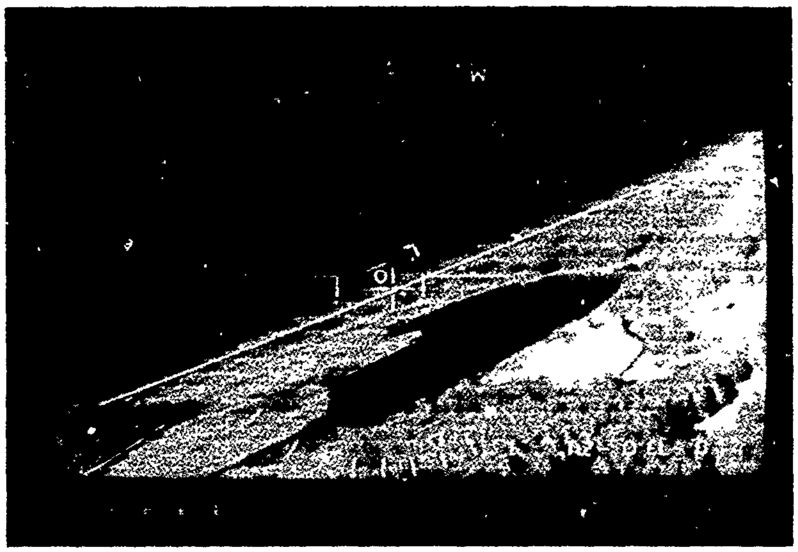


Fig. 20 Thermal image with PISA (30° x 60°) superimposed with flight symbologies

5 b Observer Visionics System

The mast-mounted observation platform OPHÊLIA (SFIM) was tested on the BO 105 helicopter. It was installed 110 cm above the rotor head. This visionics system includes a TI (TRT) called CALIPSO, based on the French Common Modules (SMT) with 42 detectors. The TI has two FOV with 5.4° x 8.1° (4x mag.) and 1.8° x 2.7° (12x mag.), (ref. 20 and 21) and a serial-parallel scanner. A TV camera (Inspectronic) and a LRF (CILAS) were the other two sensors on the two-stage gyro-stabilized and steerable platform. The platform has a coarse stabilization with torquer and fine stabilization with mirror. The diameter of the platform sphere is 600 mm and the mass above the rotor plane 120 kg. The displacement angles are: AZ ± 120° and EL -30°/+20°. The slew rate is approx. 10°/s, (figs. 21, 22 and 23).

A stationary stand pipe (30 mm Ø) containing electrical wires and two cooling tubes for Joule Thomson cooling, leads through the rotor hub to the bottom of the gear box. An 8" HDD and a 10° x 15° HUD (VDO) (modified version of ALPHA Jet HUD) were installed and tested concurrently with OPHÊLIA trials, see fig. 15. The SG was provided by VDO.

Fig. 21 BO 105 with the mast-mounted observation platform, OPHELIA, which includes a TI, an LRF and a TV camera

Fig. 22 Stabilized OPHELIA platform with sensor package installed, (ref. 20 and 21)

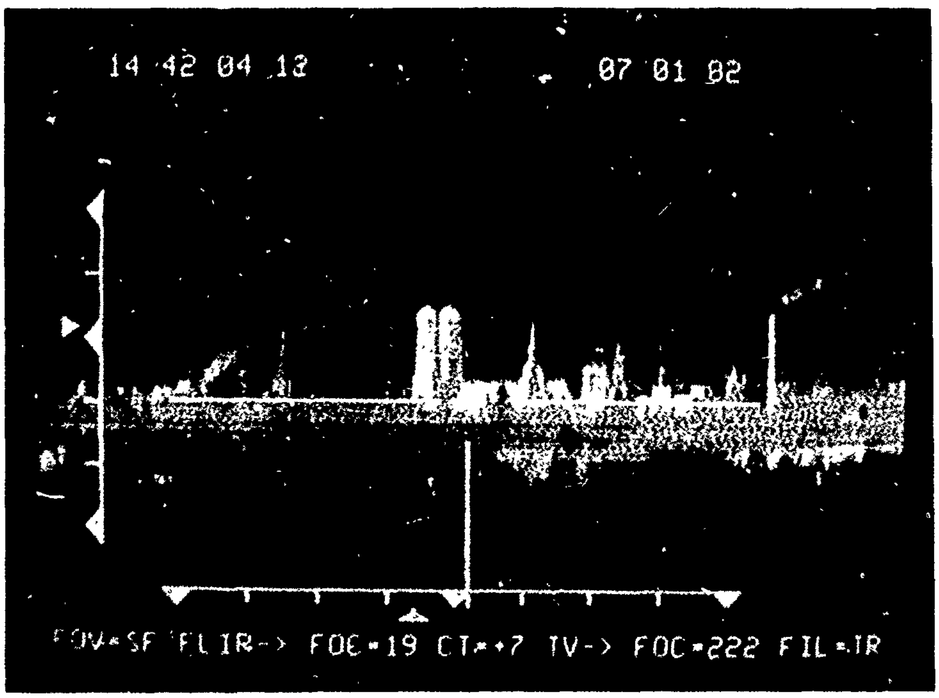


Fig. 23 Thermal image of the Munich Frauenkirche at a distance of 11.7 km taken with the CALIPSO TI, FOV 1.8° x 2.7° (ref. 21)

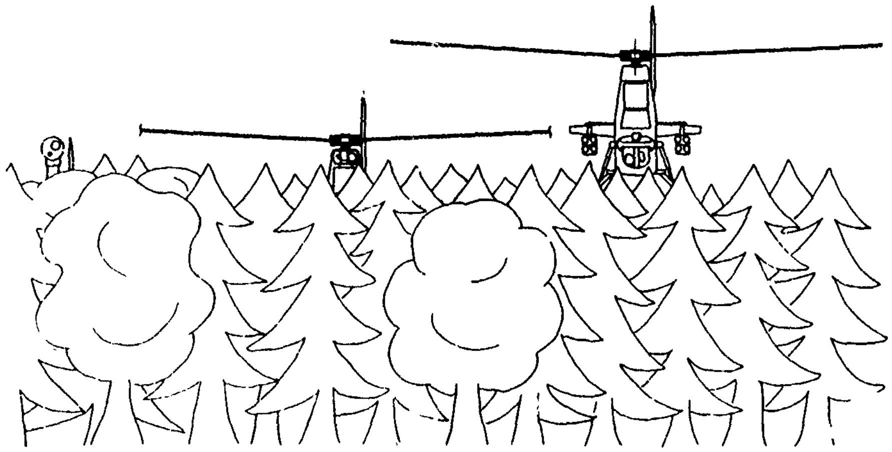


Fig. 24 Three different front silhouettes for an MMS, an RMS and an NMS helicopter hovering behind cover (ref. 10)

- Advantages of a mast-mounted sight (MMS)

The system provides an unobstructed 360° view without extensive structural modification to the fuselage and attendant center of gravity (C.G.) problems. Installation of a sensor package with LOS approx. 110 cm above the rotor plane allows for observation from the helicopter while maintaining maximum cover, a valuable advantage in military engagements. Target acquisition is possible without exposure from behind cover. The vulnerability is strongly reduced in comparison to both the nose-mounted sight (NMS) and the roof-mounted sight (RMS),(fig. 24). The visible, IR, and also radar (cross-sections) signatures of the helicopter with a MMS behind cover are relatively low. The exhaust gas of a missile does not disturb the optical window of the sight. A low vibration level was detected with the OPHELIA system.

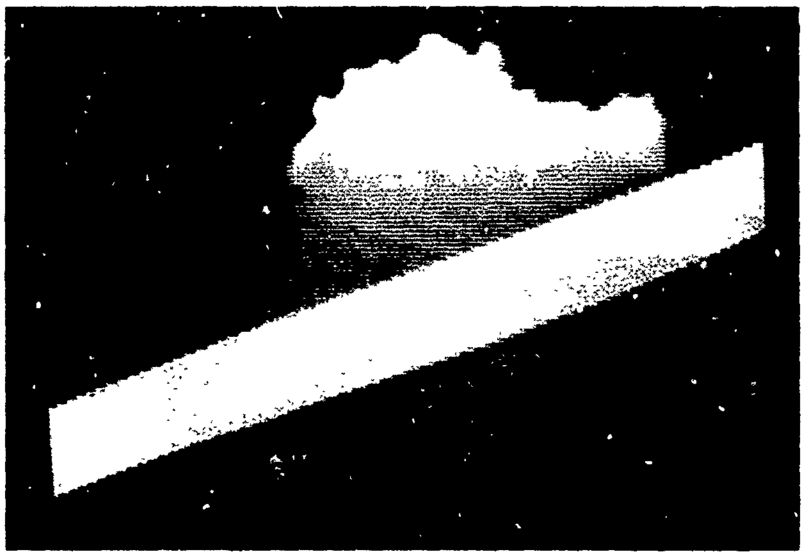


Fig. 25 A static (1/50 sec) thermal image with rotor blade influence. FLIR Systems. TI with 17° x 28° FOV and two detectors

- Disadvantages of an MMS

Through exposure of the sensor platform, the aerodynamic drag reduces the max. speed of the helicopter, with OPHELIA by approx. 5 kts. in maximum continuous forward speed. The equipment accessibility is somewhat reduced. In general, it is not possible to install a DVO, although a high resolution TV camera can solve this problem. The cue identification of an MMS against the sky is easier in the visible and the IR spectral band. This can be solved to a greater extent by cooling the MMS. Depending on the cover and the weapon, the helicopter has to bob up for weapon delivery. Problems may arise for the capture phase of guided missiles. Rotor blade interference occurs (fig. 25) if the LOS is directed downwards with a large angle of elevation EL $>-10°$, but this produces only a "chopper" effect, (ref. 21).

Problems may arise during correlation in an alignment processor between the thermal image installed in an MMS and an optical seeker head of a Fire and Forget Missile e.g. ATGW 3. In the hover mode, however, the gunner LOS is free from rotor blade influence in approx. EL = -8°, (fig. 26). This last value depends strongly on the mechanical characteristics of the MMS and the helicopter. Fig. 27 gives the FOV, the platform displacement angles and relative ranges of the PAH 2 and HAC 3G helicopter in MMS version as it will be developed in the EUROVISIONIC, Fig. 28.

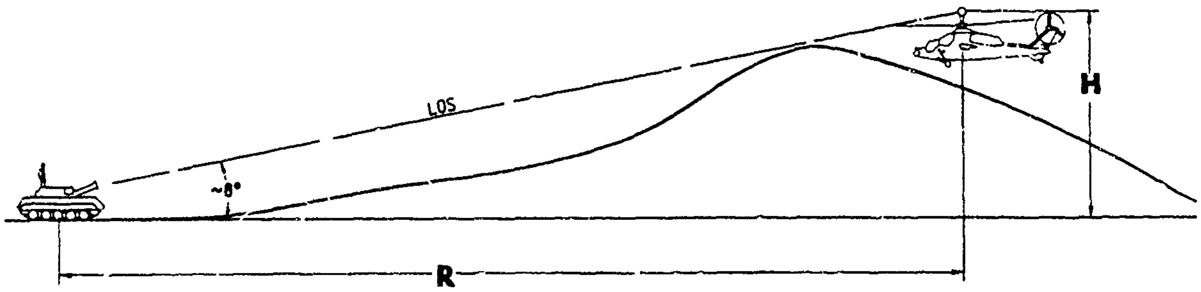


Fig. 26 MMS without rotor blade influence. The helicopter is in hover mode

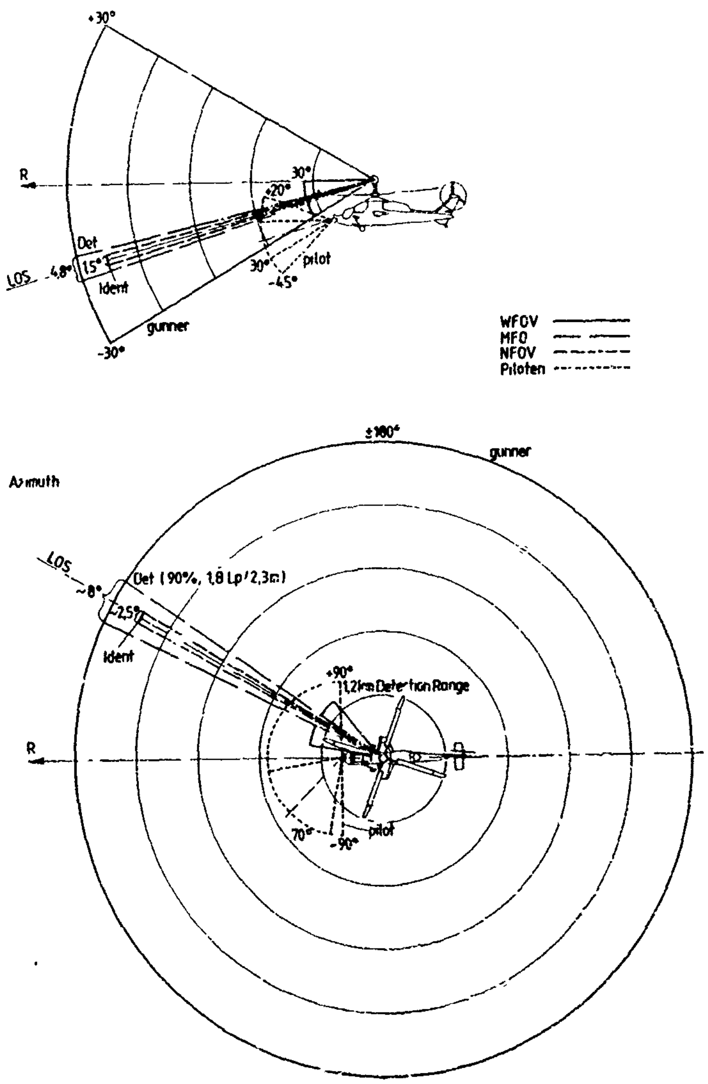


Fig. 27 FOV of a gunner FLIR on a stabilized platform in a mast-mounted sight (MMS) version

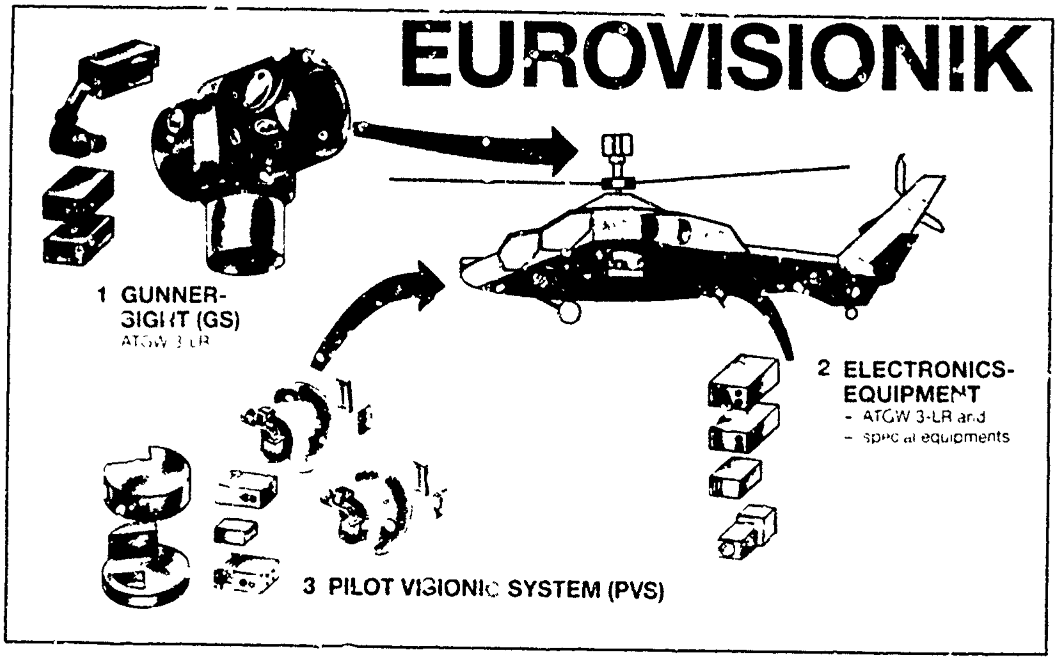


Fig. 28 EUROVISIONIK consists of the following main components:
1 Mast-mounted GS: -Stabilized steerable platform, -High resolution TI and -TV, -Laser Range Finder, -Harmonization Module, -HOT 1 µm-CCD, -Display Arm and GS-electronics
2 ELECTRONICS EQUIPMENT: -Display Processor, -Target Tracker, -HOT-components, -Video storage and -Controls
3 Nose-mounted PVS: -Steerable platform, -Wide FOV-TI, -HMS/D, -PVS-electr. and -Controls

6. CONCLUSIONS

For copilot (gunner) tasks, high resolution electro-optical night vision sensors such as TI, LLLTV and LRF (active) are necessary for reconnaissance purposes to provide a combat helicopter with 24 hour capability under virtually all weather conditions. A radar for reconnaissance purposes (as multi-sensor package) may allow operation on the battlefield even in bad weather. This sensor is, however, an active system and has a lower resolution compared with TI. A direct view optic (DVO) can only be used in the day time and at twilight. In an MMS a high resolution TV camera can be substituted for the DVO. The selected weapon systems for military applications have to be matched to high resolution visionics sensors.

For piloting tasks, a platform with a WFOV TI mounted in the helicopter nose and steerable with an HMS reduces the pilot workload and stress situation. During twilight flights, the pilots experienced no rivalry between the left eye and the right eye with its displayed image of the HMD. In the display systems, eye protection against laser and nuclear flashes should be taken into account and special optical filters used. In back-up cases, the WFOV of the gunner TI can be used for piloting tasks. NVG are a strong contender for piloting applications and offer a cost-effective solution. They can be used as redundancy for the TI sensor.

For future combat and scout helicopters a mast-mounted sight is a good solution compared to a NMS and also to a RMS. A periscopic sight with unlimited 360° viewing, low signatures behind cover, good C.G., low vulnerability and low vibration levels are possible.

7. ABBREVIATIONS

ANVIS	Aviators Night Vision Imaging System
ATGW 3	Anti Tank Guided Weapon 3rd Gen.
AZ	Azimuth
BLIP	Background-Limited Infrared Photodetection
CALIPSO	Caméra Légère Infra-rouge Pour Système OPHELIA
CCIR	European video standard with 625 lines, 25 Hz frame rate
CEP	Circular Error Probability
CG	Center of Gravity
CM	Common Modules
CRT	Cathode Ray Tube
DC	Direct Current
DVO	Direct View Optics
EIA	American video standard with 525 or 875 lines, 30 Hz frame rate
EL	Electro-luminiscent
EL	Elevation
EMDG	Euromissile Dynamics Group
EO	Electro Optical
EP	Entrance Pupil
FLIR	Forward Looking Infrared (TI)
FOV	Field Of View
GaAlAs	Gallium Aluminium Arsenic
Ge	Germanium
HAC 3G	Helicopter Anti Char 3rd Generation
HDD	Head-Down Display
HgCdTe	Mercury Cadmium Telluride (MCT)
HMD	Helmet-Mounted Display
HMS	Helmet-Mounted Sight
HMS/D	Helmet-Mounted Sight/Display
IFOV	Instantaneous Field Of View
IR	Infrared
IRCCD	Infrared Charge Coupled Device
ISV	Intensified Silicon Vidicons
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
LHX	Light Helicopter X-Program
LLLTV	Low Light Level TV Camera
LOS	Line Of Sight
LRF/D	Laser Range Finder/Designator
MCP	Micro-Channel Plate
MFD	Multi-Function Display
MFOV	Medium Field Of View
MIRA	MILAN Infrarot Adapter
MMS	Mast-Mounted Sight
MRT	Minimum Resolvable Temperature Difference
MTF	Modulation Transfer Function
NET	Noise Equivalent Temperature Difference
NFOV	Narrow Field Of View
NMS	Nose-Mounted Sight
NOE	Nap of Earth
NVG	Night Vision Goggles
OPHELIA	Optique sur Plate-forme HELIcoptère Allemand
PAH 2	Panzer Abwehr-Hubschrauber (anti tank helicopter) 2nd gereration
PC	Photoconductive detectors
PISA	Piloten Infrarot Sicht-Anlage (Pilots Infrared Sighting Ability)
PV	Photovoltaic detectors
PVS	Pilot Vision System and Pilot Visionic System
RADAR	Radio Detection and Ranging
RMS	Root Mean Square
SG	Symbol Generator
Si	Silicon
SIT	Silicon Intensified Target
SiTF	Signal Transfer Function
SPRITE	Signal Processing In The Element, Tom Elliott Device
SMT	Systéme Modulaire Thermique (French Common Module)
TI	Thermal Imager (FLIR)
TV	Television
WFOV	Wide Field Of View
ZnSe	Zinc Selenide

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ANNEX 1

RADIOMETRIC UNITS (index e)			PHOTOMETRIC UNITS (index v)		
name	symbol	units	name	symbol	units
area, projected area	A_1, A_2	m^2	area, projected area	A_1, A_2	m^2
range	R	m	range	R	m
solid angle	$\Omega \sim A_2/R^2$	sr	solid angle	$\Omega \sim A_2/R^2$	sr
1. Radiant intensity	$I_e = \partial\phi_e/\partial\Omega$	W/sr	1. Luminous intensity	$I_v = \partial\phi_v/\partial\Omega$	cd (Candela)
2. Radiant power (flux)	$\phi_e = \partial Q_e/\partial t$	W (Watt)	2. Luminous (light) flux	$\phi_v = \partial Q_v/\partial t$	cd.sr = lm (Lumen)
3. Radiant energy	Q_e	W.s = J (Joule)	3. Quantity of light	Q_v	lm.s
4. Radiance	$L_e = \partial I_e/\partial A_1$	$W/sr/m^2$	4. Luminance	$L_v = \partial I_v/\partial A_1$	cd/m^2 (ftL)*
5. Radiant emittance (exitance)	$M_e = \partial\phi_e/\partial A_1$	W/m^2	5. Luminous exitance	$M_v = \partial\phi_v/\partial A_1$	lm/m^2
6. Irradiance	$E_e = \partial\phi_e/\partial A_2$	W/m^2	6. Illumination	$E_v = \partial\phi_v/\partial A_2$	lm/m^2 = Lux**
7. Radiant exposure	$H_e = \partial Q_e/\partial A_2$	$W.s/m^2$	7. Exposure	$H_v = \partial Q_v/\partial A_2$	$lm.s/m^2$
8. Radiant efficiency	η_e	%	8. Luminous efficiency	$\eta_v = \partial\phi_v/\partial\phi_e$	lm/W

* 1 ft-L (foot Lambert) = 3.426 cd/m^2
** 1 ft-c (foot candle) = 10.764 Lux

Table 5 Important radiometric and photometric units (ref. 2)

OPERATIONAL EXPERIENCES WITH NIGHT VISION GOGGLES IN HELICOPTER LOW-LEVEL FLIGHT AT NIGHT

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SUMMARY

This paper describes the operational marginal conditions with regard to the threat analysis in the Central European theatre.

This is supplemented by a presentation of the technological and physical aspects of the available visual sensors, such as helmet-mounted night vision goggles (NVG), low light level television (LLLTV), and forward-looking infrared (FLIR) and their employment as pilotage aids within the helicopter cockpit.

Also, a description is given of the work capabilities and limitations inherent with the employment of electro-optical vision aids using representations on slides. This involves a comparison of the visual capabilities of the unaided eye during low-level flight with moon illumination at night, conditions during reduced light levels, and viewing the same scene with electro-optical sensors.

The requirement for glare protection within the cockpit is discussed and different solutions are represented. An exceptional and difficult problem to solve is currently presented by positive position fixing under the given circumstances. Aids and procedures to improve navigation have been devised and are now successfully in use.

Finally, the briefing discusses the results of interviews with helicopter pilots, who have long-term experience with the use of helmet-mounted night vision goggles.

I. INTRODUCTION

The results compiled for this briefing are based on experiences obtained from practical flight operations with military helicopters over a period of about eight years. These were mainly missions flown during test and training flights in the scope of night low-level flights, which were conducted at the German Army Aviation School and in individual cases with partners of the Western Alliance. Studies were exclusively related to the mission capabilities of military helicopters under consideration of military marginal conditions.

Viewgraph 1. Expectations on the Central European theatre

The generally known expectations on the Central European theatre such as

- conduct of a sustained combat for several days,
- massed and highly mobile occurance of ground-based enemy forces on a wide frontage,
- threat by strong frontal aviation forces, combat helicopters, and airborne forces,
- employment of highly advanced reconnaissance means,
- and precision electronically guided weapons on the enemy side,

lead to requirements, which in addition to other reactions necessitate an increase in the combat efficiency of Army aviation.

A first step to be taken in order to achieve this, is the capability to pilot helicopters even in darkness and reduced visibility conditions utilizing terrain masking techniques.

Special significance for future mission profiles results from the essential improvement of reconnaissance means on the enemy side.

Even outside the range of an immediate threat by enemy weapons effects, an early identification of friendly helicopters through enemy reconnaissance means will present a serious hazard to friendly intentions.

Viewgraph 2. Employment of helicopters on the battlefield

It must be anticipated that utilizing altitudes of above 300 ft agl (approx. 100 m) within the corps rear area is no longer possible. During flight maneuvers in the direction of the forward edge of the battle area (FEBA), 150 ft agl (approx. 50 m) within the division area and 100 ft agl (approx. 30 m) within the brigade sector must not be exceeded. In the forward brigade sector and in the immediate vicinity of the FEBA, altitudes around 10 ft agl (approx. 3 m) become necessary in order to avoid enemy reconnaissance and fires.

In addition to this, prohibited zones and flight corridors will be established on the battlefield, which must exactly be adhered to.

It can be assumed that operational flights on the battlefield are among the missions with a special degree of difficulty; added-on difficulties result from the employment by night and under the aforesaid conditions.

It seems an undispensible requirement that the results obtained during night low-level flights be integrated into the planning and design of future military helicopter cockpits.

II. VIEWING CAPABILITIES

Low-altitude night low-level flights, especially those conducted within the background of obstacles, cannot be performed as conventional instrument flights. The reasons for this are obvious and need no detailed discussion. Visual flight in darkness and reduced meterological conditions is substantially governed by the available viewing capabilities.

In addition to the image intensifer night vision goggles (NVG), forward looking infrared (FLIR) and low light level television (LLLTV) can be used as sensors, if they provide quasi-optical vision. An imperative requirement for flights, which are to be conducted within the obstacle background, however, is a quick-swivel mount for the sensor (more than 90°/sec in conjunction with a transmission of the user's head movement and an image display located immediately in front of the eyes (HMSD: Helmet Mounted Sight Display).

In addition to the cost for the high technological effort, two other reasons prevent use of FLIR as the sole piloting aid, at present.

- In contrast to manifold claims, a large independence of weather conditions cannot be achieved. The radii of most fog droplets in natural fog range from 2 micrometers to 20 micrometers, the maxima of their frequency distribution being between 5 micrometers and 15 micrometers. Since the maximum diffusion effect of a droplet occurs at radius = wavelength, these droplets are very efficient infrared diffusors; i.e. in natural fog, thermal imaging will fail. /Gae 75/

- Thermal imaging devices use the thermal contrast that exists between targets and their surroundings. The quality of the device depends on its thermal resolution capability. It is possible to realize values around 0.3°K delta t (temperature difference between the object and its background). It is very disadvantageous that objects (obstacles) in the scene can change their delta t rapidly. If delta t is less than 0.3°K, obstacles will no longer be displayed. Sometimes this is also true, when the thermal image has left a good image impression with the pilot. It appears very critical that the pilot is unable to notice this deterioration of environmental conditions.

Viewgraph 3. Helmet-mounted NVG

Third generation night vision goggles provide a night low-level flying capability down to approximately 0.2 mLx.

Viewgraph 4. Foot Candles versus millilux

A gradual impairment of recognition range occurs at ambient light levels below 0.8 mLx. Although these devices penetrate atmospheric turbities better than do second generation NVGs because of their spectral sensitivity shift into the red, they are subject to weather induced effects.

These are mainly phenomena, which cause a direct loss of ambient light level (thick rain clouds).

It seems favourable that the pilot is able to clearly distinguish any deterioration of light conditions by an increase in tube noise and that he can adjust himself to the situation.

Presently, the use of night vision goggles as sensors for night low-level flights is the simplest, most efficient, and cost-effective approach to the improvement of viewing capabilities.

As improvement of night vision sensors through optimization and combination of thermal imaging and image intensifier devices is possible, the currently available knowledge is of special importance to the design of future cockpits.

Viewgraph 5. Restrictions to viewing capabilities

Although the aforesaid sensors realize night vision, restrictions to viewing capabilities result from

- limited geometrical resolution,
- limitation of the field of vision to 40°,
- unfavourable perspective viewing angles into the terrain due to low altitude,
- physiological effects produced by additional weight on the head.

III. DESCRIPTION OF OPERATIONAL CAPABILITIES AND LIMITATIONS BY PRESENTATION OF EXAMPLES

As an example for the image impression of the unaided eye you will be shown the following slides.

Slide 1. View with the unaided eye

The dark-adapted eye has no colour discriminating capability. Therefore, the outside scene is viewed as an image of graduated greytones. The natural field of vision can be utilized. Moonlight generally produces a high ambient illumination, which permits use of vision techniques similar to those for day conditions.

For comparison, the next slide shows the same terrain as viewed through the helmet-mounted night vision goggles.

Slide 2. View with the helmet-mounted night vision goggles

Limitation of the field of vision to a sector of 40° represents the obviously most important difference to the preceding image. Moreover, a deterioration of visual acuity and the resulting reduction in resolution of fine structures is evident.

The image impression shown here corresponds to illumination conditions above 15 mLx. A similar image impression is provided on the HMSD of the FLIR, when good thermal contrast conditions exist.

Additional slides are to demonstrate the conditions prevailing during night low-level flights and the resulting problems.

Slide 3. Tall trees viewed with the unaided eye

Flight attitude can be determined by reference to the vertical vegetation. Structures on the ground and the field in the right-hand background indicate the terrain configuration. The helicopter's position is right in front of the trees at treetop level about 75 ft agl.

This important piloting information can be obtained by a single glance into the terrain.

Slide 4. Tall trees viewed with the helmet-mounted NVGs

The small image sector of 40° merely permits judgement of the aircraft's flight attitude with reference to the vertically grown trees. Identification of the terrain configuration is possible, when the field of vision is artificially extended by raising and turning the pilot's head.

This illustrates why a fixed sensor is of no use in this situation. A sensor, which is swivelled by means of a manual control in conjunction with a presentation of the image on a head-down display (HDD), is useless, too, because the image, which is running on the HDD during azimuth movement of the sensor, cannot correctly be evaluated.

Judgement of altitude can also be achieved through azimuth movement of the head. In these good sensor visibility conditions, the eyes are virtually forced to focus on the tops of the trees which stand close to the right-hand side of the helicopter.

Flight over these obstacles is performed with visual contact in order to pass over these obstructions with the minimum possible clearance so as not to have to leave the masking offered by the terrain. Only when light or thermal conditions produce too poor images, will the aircrew use the height indication of the radar altimeter.

Slide 5. Over th orest with the unaided eye

In this situation, the focus of the unaided eye jumps from treetop to treetop. Flight altitude and airspeed are judged by comparison of the relative motion of individual tree structures with reference to one another. An unrestricted view into the area immediately in front of the helicopter is required in order to be able to maintain as low an altitude as possible.

Slide 6. Over the forest with helmet-mounted NVGs

Major azimuth movement of the sensor is necessary to obtain a sufficient number of usable information for the evaluation of forward speed, altitude, terrain configuration and obstacle clearance.

When a helmet tracker is used to control sensor movement, the pilot will know the sensor's direction of sight from the position of his head. Quasi-natural optical viewing is possible. This, however, has a definite requirement for maximum azimuth ranges in conjunction with high slewing rates.

IV. GLARE EFFECTS WITHIN THE COCKPIT

The employment of night vision goggles as night vision sensors for helicopter low-level flight generates an imperative requirement for avoidance of glare effects and reflections within the helicopter cockpit as well as on its front and side windscreens.

It is just within the range of decreasing sensor performance - i.e. at low ambient light levels of less than 0.8 mLx, when the recognizability of fine structures, such as leafless branches, wire hazards, etc. is largely reduced anyway - that disturbing reflections have very negative effects. Under those conditions, the disturbance may cause loss of outside view.

The conventional red instrument lighting is incompatible with the use of image intensifiers.

Viewgraph 6. Employment of helmet-mounted NVGs in the cockpit

As the installed instrument lighting is not compatible with NVGs, it will be switched off during flight operations. If instrument information is required, it will be provided by using a spotlight, which is actuated via a lip switch. Readings of displays can be taken in the free field of vision with direct view to the instruments.

Extensive studies conducted by the U.S. Army have resulted in the introduction of a blue-green cockpit and instrument lighting. /Fra 83/

Disturbing reflections on the front and side windscreens are prevented in this way indeed. Glare effects caused by the lighted instruments do not occur. Still, an impairment of visual efficiency with NVGs can subjectively be observed at ambient light levels below 3 mLx. It is assumed that the relatively high light level within the cockpit affects the eyes directly, because helmet-mounted goggles allow unrestricted incidence of light into the eye.

This negative fact is of special importance, because about 55 % of all nights in Europe have a darkness level of below 2 mLx.

We feel that the approach to instrument lighting adopted by French Army aviation is more favourable. Graduations, figures, and needles of instruments are coated with fluorescent paint and are lighted by UV light during night low-level flight. Displays can be distinguished well without impairment of visual capabilities and they provide excellent legibility in the dark cockpit.

V. NAVIGATIONAL CAPABILITIES

Slide 7. Navigation

Under the given conditions, such as

Viewgraph 7. Factors affecting navigation

- reduced visual capabilities through electro-optical sensors,
- poor viewing capabilities into the terrain due to low flight altitude,
- lack of radio navigation means,
- inaccurate heading information due to large variations of the earth's magnetic field during flight close to the ground,
- decreased legibility of the map image due to darkness and helicopter vibrations and
- mental errors of the aircrew

positive position fixing presents an extraordinary and difficult to solve problem.

First, flying was possible only on flight routes, which had been learned by heart. Special difficulties resulted always when flights were to be conducted below the height of wire hazards. Special flight procedures developed for the approach and overflying of wire hazards indicated the new direction to be taken.

The introduction of the helmet-mounted NVG provided the capability to read navigational charts, because viewing the illuminated map sheet with the naked eye was now possible.

Viewgraph 8. Night Map Display

In order to avoid the aforementioned glare effects, the German Army Aviation School developed the night map reading device and introduced it into Army aviation. In addition to an effective light shielding of the map sheet lighting, ophthalmological advantages are provided by a magnifying glass, which is installed in the device and magnifies the map image. The timer integrated into the device facilitates timekeeping enroute.

The display can be attached to the cockpit frame by means of an individually adjustable supporting arm. This permits limited operation of the display without using one's hands.

Using this display permits night low-level navigation

- along prominent navigational lines,
- as dead-reckoning over legs with few navigational features,
- as mixed navigational procedures over extended legs.

Accurately maintained obstruction charts of the area, in which the night low-level flight is to be conducted, are an essential requirement for all such flights.

Unlike navigation during day low-level flights, navigation by night causes additional difficulties, because prominent terrain features, which are indicated on the map image, are more difficult to identify and are available in smaller numbers for correlation with the map image. This extreme small-scale orientation in 500-meter increments presents an extremely high work load.

The risk of mental errors and resulting geographic disorientation appears very high under operational conditions. The situation during flights below wire hazard height in the free tactical sequence of operations seems to be particularly critical.

Therefore, the enhancement of flight safety during night low-level flights requires the introduction of automatically operated map displays.

With the introduction of the weapons systems VBH/PAH (liaison and observation helicopter/antitank helicopter) into the Army aviation forces self-contained navigation systems were available for the first time. As a result the aircrews experienced some reduction in workload, which was an imperative requirement in the light of a new division of responsibilities.

Employment for night low-level flight and the navigational problems generated in conjunction with the use of electro-optical sensors clearly showed that the doppler navigation system alone is insufficient, because

- the analog display of the heading (SHIU) merely provides a directional indication with reference to the destination;

- alphanumeric information displayed on the LED field (CDU) cannot directly be correlated with the map image.

Continous correlation of the map image and terrain is necessary to be able to determine deviations from the desired track in time. Added difficulty results from the requirement to locate a navigational feature on the map, which has been observed in the terrain, and subsequently to compare it with the alphanumeric display in order to be able to determine and correct any deviation occuring in the system. This causes such a high workload that no other task can be accomplished in addition to navigation.

As the doppler navigation system's indicating accuracy is mainly depending on the accuracy of the heading values, which, however, are greatly affected by variations of the earth's magnetic field, the system must be updated at regular intervals, in order to operate with a sufficient accurarcy. A high indicating accuracy is required to locate obstacles, which are difficult to see, such as overland cables, using the navigation system as an aid. Errors of the system can be identified only by a real-time comparison of the planned and actual position on the map. This is only possible by supplementing the navigation system with an automatic map display.

Viewgraph 9. Automatic Map Display

The display of the actual position on the map image is important in many respects.

- navigational features near the flight route can very quickly be located on the map image,

- deviations from the planned course can be recognized in real time,

- system induced deviations are recognized and can easily be updated,

- because of the high indicating accuracy provided by system checks in comparison with the overflown terrain, obstacles, which are difficult to detect, can positively be located and overcome,

- it is possible to safely follow narrow flying lanes matched to the contours of the terrain, to avoid known positions and to fly around prohibited areas, while avoiding major detours,

- the aircrew's workload is significantly reduced; additional task, such as maintaining the situation map, handling of tactical voice radio communications, etc., can be accomplished.

To sum up, it can be said that extensive use of self-contained navigation systems is possible only in conjunction with automatic map displays.

VI. PHYSIOLOGICAL AND PSYCHOLOGICAL ASPECTS

The doctrine of a battle sustained over 72 and more hours by the potential enemy, forces helicopter crews into extended periods of stay within the cockpit. The optimization of the cockpit as a work station gains utmost importance in the light of the special stress caused by unfavourable working conditions during night low-level flights such as

Viewgraph 10.

- restricted vision,

- additional weight to carry on the head,

- high degree of psychological and physiological stress due to low flight altitudes in the area of obstacles,

- stress produced by accummulation of tasks in a dark cockpit,

- threat by enemy reconnaissance means and weapons effect.

From the German Army Aviation Chief Flight Surgeon's point of view some problems concerning the description of physiological aspects are produced by the fact that -

- introduction into service of the helmet-mounted night vision goggle and the associated stress can only be observed since a relatively short period of time;

- only subjective statements on personal experience are available; and

- only few parameters are available, which can be used for evaluation.

Increased mass acting on the head due to helmet-mounted night vision goggles,

Viewgraph 11. Helmet-mounted Sight

Viewgraph 12. Night Helmet

helmet-mounted sight or other future imaging devices for night vision systems in conjunction with helicopter aircrew NBC protective equipment will put stress on the vertebral system and on the muscles in the back of the neck and of the muscles of the back. The vibrations transmitted to the human body cause rapid fatigue and reduce mission times.

First of all, spasms of the muscles of the back and the neck become noticeable, which are caused by non-physiological forward shifting of the weight. The impact of this adverse center-of-gravity position and the additional stress induced on the supporting system are evidenced by indurations and strains.

The additional weight of the night vision goggle alone produces

- strengthening of the muscles,

- a certain dissymmetry of the supporting system caused by muscular development,

- most probably no damage to bones and intervertebral disks.

The situation may be different, if the additional weight is examined in combination with the helicopter's characteristic vibrations. However, it is not possible to make any statements concerning this subject matter, since systematic studies have not been conducted and substantiated findings are not available yet. In the long run, one should consider possible changes on the small joints in the area of the vertebral column.

So far, serious problems in the physiological scope have not been encountered.

Adverse effects, caused by employment of night vision goggles, which undoubtedly do exist, can be summarized as follows:

- A sound cervical vertebral column sometimes may suffer from minor complaints, but will not undergo any changes;

- existing changes on the cervical vertebral column will significantly increase previous troubles, when night vision goggles are used for flight operations;

- the question about processes and influences on metabolism of the cartilaginous layer of the intervertebral joints is still unsettled.
  X-ray depiction of the small intervertebral joints using oblique photography of the cervical vertebral column, which permits monitoring possible changes occuring among the involved personnel is an imperative requirement for the initial measures.

In addition to this, vibrations of given frequencies will cause impairment of visual efficiency. In 1982, appropriate findings were presented by Emil Hartung.

I quote:

Under application of vertical vibration load, substantial reductions of vision could be proved within two frequency bands. On the one hand, this is true for the resonance range of the human body around 4 Hz. Although a significant reduction in visual acuity could not be determined , the acquisition times did partly increase - during recognition of numeral combinations - to the 25-fold. On the other hand, a relatively large reduction in the resonance range of the eye (16-31.5 Hz) of about 10 % could be demonstrated. Also a maximum increase in optical acquisiton times can be found within this frequency range.

The statement continues:

Upon exposure to vibrations in the horizontal y-direction all visual efficiency tests showed the comparatively largest impairment with particularly significant reductions in visual acuity of up to 22 % found at vibration loads with frequencies of 25, 31.5 and 40 Hz. Also

within this frequency range, extreme increase in optical acquisition times resulted during the Landolt ring tests, which amounted to the 56-fold as compared to rest conditions. /Har 82/

Rigid main rotor systems seem to be particularly critical in this respects, because feelings of discomfort ranging as far as air sickness are observed particularly frequently in conjunction with this type rotor systems.

Psychological stress can now be discussed only at a glance. A detailed discussion is given in the report of the German Air Force Institute of Aviation Medicine, parts of which will be quoted here.

The stresses induced to the helicopter pilot by flying with NVG are obvious: Reduced visibility conditions, restricted perception of attitude and depth, risk of optical illusions (autokinetic effect, confusion of ground lights with lights in the sky, etc.), briefly, to an even higher degree than during low-level flights in daylight, the "continous struggle for a stable field of reference" requires the pilot's increased watchfulness and permanent presence during the entire mission (about 1 1/2 h). This produces an increased level of emotional stress. The permanent strain of the crew caused by continuous operation of the controls and the increased efforts to timely recognize obstacles are subjective indicators of this. ("There isn't any moment, which permits to unwind for a second or two")!

Short "breathers" are impossible for another reason. Although NVG missions in a certain way are similiar to low-level flights in adverse weather conditions, they are different in one important respect: As visibility is being restricted the helicopter pilot usually will trade proximity to the ground for an increased obstacle clearance. In the same situation, the NVG aviator will descend even more and reduce his obstacle clearance in order to improve recognition. Thus he gets into the contradiction of improved visibiliy versus increased flight hazards. As a result, increased emotional stress is added to the previously high degree of physical and mental stress.

Very instructive with respect to problem solving in this context is the verbal coordination maintained between both pilots throughout the entire mission, in order to verify and supplement information and thus providing safety as well as reducing emotional stress. This dialogue is experienced as being so important, that as soon as it is interrupted or discrepancies occur, a reversal procedure is initiated to return to the last orientation point which had been positively identified.

The effects reported by pilots can be summarized in two complexes. One comprises the individual reactions to the high pilot work loads, mental and emotional stresses connected directly to NVG operations. The other comprises social problems resulting from duty hour regulations.

Higher heart rates, palpitations, a dry mouth, and increased secretion of sweat ("subaxillary perspiration is the done thing among NVG aviators") are mentioned as objectivable symptoms. On the one hand it appears as if the postflight emotional stress is reduced with increasing NVG experience, but on the other hand even veteran NVG flight instructors experience undeminished stress during reconnaissance missions and on frequent flights under marginal lighting conditions within the range of 1.0 to 0.5 millilux.

After their flight, most NVG pilots feel an intensive urge to talk to others. Pilots meet at the coffee shop to have a beer or two and discuss their previous mission, special occurrences during the flight in a detailedness exceeding the scope of normal debriefings. In fact, the persons involved are quite aware that they are "blowing off steam" trying to "get rid of troublesome experiences".

NVG flights, to a much higher extent than other missions, require "extremely good cooperation" and the conviction to be able to "absolutely rely on one another". This is why the quality of interpersonal relations gains eminent importance.

In addition to the problems related directly to NVG flying, which can be classified as individual-specific responses of pilots to the high mental and emotional stress, NVG flying generates problems, which are related to it only indirectly. This means problems within families and changes in other social relations.

The disturbance of the natural night/day cycle is not unproblematic, either. At night, when the organism is switched to rest and relief, the pilots have to provide maximum performance, whereas in the morning, when a physiologically high readiness to perform would be given, the rest period is extended. Also many pilots are unable to find the necessary rest, since beginning day activities will make it impossible to continue sleeping. So pilots reporting to be more hectic, nervous, and irritable than they used to be are no surprise.

The survey shows, that night low-level flying with NVGs has various effects and implies a series of problems and difficulties, whose solution has been only partially successful as yet. From our point of view the pilots have developed quite efficient strategies to cope with the direct, mission specific loads and stresses. The variety of measures spontaneously taken by the individual pilot, are basically designed to reduce tension and to subdue the high level of emotional stress especially after this kind of mission. These could be supplemented by a valuable method through systematic introduction into psychological relaxation techniques (autogenic training, progressive relaxation of muscles after Jacobson, etc.). To what extent

this could be realized in terms of organization, we cannot assess. It should be stressed, however, that a reduction of muscular tension has been proven to effect an emotional relaxation, which helps avoiding damage caused by chronic stress.

Dealing with the problems caused by shift operation does not seem to work as smooth as this. Organizational measures (regulation of duty hours, limitation of flight hours, etc.) may bring about a reduction of pilot work loads, but they alone are not sufficient - as our findings show - to solve the problems. This turns the focus from organizational conditions to social psychological implications of shift work. The different kind of work does not only affect pilots but also their families and other social contacts. It necessitates changes in the individual conduct of life and causes deep changes within family and nonfamily relations. It is suggested to establish an instruction, which deals with the anticipated everyday problems of shift work and possible solutions, in order not to leave the individual on his own, when trying to solve these problems.

As for the rest, one should start from the fact that the Bückeburg situation is not representative for the forces. Introduction of the NVG is scarcely likely to necessitate shift duty within the forces for years. The problem within the forces will rather be that frequent changes between day and night shifts cannot be avoided and that the factor of interpersonal relations within an aircrew cannot very much be taken into account. However, this will also increase the risk of decompensation phenomena. Further analyses of behaviour and collection of physiological and psychological data are required to find measures for the solutions of these problems.

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EVALUATION OF HELICOPTER HELMET-MOUNTED DISPLAY MOCK-UP

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ABSTRACT

A psychophysiological investigation was conducted on a mockup to evaluate a helmet-mounted FLIR display. This experiment included laboratory and inflight testing. Laboratory testing : angular visual acuity, contour perception and stereoscopic acuity were tested. Electrooculography was used to test binocular behavior under monocular stimulation (inter-ocular synergy, binocular rivalry, optokinetic nystagmus). Results showed decreased angular and stereoscopic acuity, and provided a better understanding of eye activity components in this situation. Inflight testing : stressful perception was evidenced during low level helicopter flight, which can be either an overestimation of distances and altitude by active pilots, or an underestimation of these parameters by passive pilots. An illusory sensation was observed under certain binocular uses of helmet-mounted displays. It concerns contour vision. Hypotheses are formulated for those various sensory changes.

INTRODUCTION

The evolution of military tactics and strategies implies a great increase in the number of nighttime operations. The helicopter, with its many and various uses, does not escape this rule. Man's visual functions in night vision do not allow totally safe tactical flights. Alternative technologies have been developed (MENU et al., 8) among which thermal imagery took a choice place. It uses a transducer and an electronic chain which transform infra-red radiation into emissions visible by the human eye. This radiation is emitted by a CRT which, at the very beginning, was affixed onto the instrument panel. The thermal camera, with reduced field, had to be mobile to explore the surrounding space. Its sight axis was initially manually controlled, which, for the pilot, meant observation of lateral space. The camera was, therefore, not controlled by gaze direction. To alleviate such an inconvenience, the concept of "helmet-mounted display" was developed. The point is to always place in front of the eye the landscape spreading in the axis of the head...

The thermal camera, located for given reasons outside the cockpit, is controlled by head motion. Once processed, its image is displayed on a pilot's helmet-mounted display.

The state of technologies and their costs induced engineers to mount -in a first phase- only one display in front of one eye. Consequences on visual perception and flying had to be studied. A mockup simulating this situation was made available to our team to conduct the following evaluation.

1. MATERIALS AND METHODS

1.1. HELMET-MOUNTED DISPLAY

The tested equipment called "helmet-mounted display" was the mockup of a system for optical information display incorporated to a helmet (Fig. 1). It includes a flight helmet complete with :

- a small TV camera,
- a multifunction (stroke and rasterscanning) screen, with monochromous green signal emitted for both scannings,
- an optical block including a semi-reflecting prism for the display of collimated TV images at the infinite, in front of the pilot's right eye. The visual field is 30° X 40°. The prism permits optical superimposition of synthetic and outside world images. However, superimposition of the TV image can only be achieved for objects located at a distance of at least 10 m (this is due to the parallax between camera and right eye).

Various adjustment devices insure equipment compatibility with morphological variability of the persons wearing it.

1.2. PHYSICAL CHARACTERISTICS OF THE SIMULATION

In natural vision, stimulation has similar form, light level, color and movement for both eyes, which is no longer the case with a helmet-mounted display.

Changes are of two types :

1.2.1. Different stimulations for left and right eye

1.2.1.1. Luminance stimulating the right eye can only change by 30-150 cd.m-2, whereas the left eye can be exposed to a much wider range of luminances, the range of the natural world.

1.2.1.2. The right eye receives

- a monochromous green TV image (625 lines), intermittent in time and space,

- poorer image definition (fewer dots and reduced contrast range compared to reality),

- this virtual image is always collimated at the infinite, whatever the object distance may be.

Such are the differences between right eye stimulation and stimulation received by the left eye which is a direct view of the outside world.

1.2.2. Monocular, binocular or third type situations

Mockup design allows a number of situations, some which are for the least unusual, with more or less predictable consequences. Only those which correspond to relevant use of the device were evaluated.

Monocular vision : left eye closed, right eye stimulated by the image of the TV tube with no direct vision of outside world. Terrain perception cannot result from stereoscopy ; only cortical factors of this perception are used, and on a deteriorated image.

Binocular vision : the left eye sees the outside world naturally or through an attenuating neutral filter. Colors and contrast range are maintained. This filter is used when the predictable difference in luminance between the two eyes is excessive.

The right visual channel is in a very unusual situation. It receives an image picked up by a sensor located on the left of the left eye.

The third type should be described as bi-ocularity rather than binocularity in the classical sense of the word.

Given such a situation : monocularity with artificial image, false binocularity, literature data do not totally answer the question : "Is it possible to fly a helicopter under operational conditions using this device ?".

The little data available provide a framework for experimentation and highlight crucial points whose influence must be tested. LEGRAND (7) demonstrates the role, in stereoscopic perception, of visual acuity, disparity of retinal images which must remain coherent. Among all factors quoted by LAYCOCK (6) as having a role in binocular rivalry, some are implemented by the "helmet-mounted display" : luminance difference, difference in the complexity of the two images, as well as accommodation mechanisms. All these factors are related to the fact that control centers are assumed to be identical for both eyes. Cognitive problems related to the operational use of these devices should also be taken into consideration : different types of more or less complex information processing.

Most frequently, approaches are based either upon laboratory work (fundamental physiology or pure technology), or upon field studies. These two types of studies are rarely carried out by the same teams.

Being aware of the value of another approach, we designed the mockup evaluation protocol according to the following procedure :

- laboratory study of visual functions which can be altered by the wear of a helmet mounted display, followed by

- inflight study of some of these functions and their integration to aviation tasks.

Experimental equipment and protocol were designed to take this schedule into account.

1.3. SUBJECTS

Fifteen subjects (age 29-48) participated in the two stages of this experiment. They were either civilian or military flying personnel, all involved in test flying, and with 2,000-5,500 flight hours. Visual functions were naturally satisfactory in this population of flying personnel.

2. LABORATORY TESTING OF "HELMET MOUNTED DISPLAY"

The helmet mounted display was a test mockup. A distinction should be made between :

- observations depending on used testing materials. Pilot's acuity in terms of angular and stereoscopic acuity at the image center and periphery is related to the camera and the optical device ;

- observations related to monocular situation and binocular rivalry, therefore relatively independent of the above observations although it does not seem possible to really separate acuity from binocular rivalry.

Finally, all these observations are also designed to serve as reference for comparison with other image display systems (TV camera + TV tube) or binocular or bi-ocular displays (image generated by a camera and simultaneously displayed in front of both eyes).

2.1. EXPERIMENTS RELATED TO REAL IMAGE TRANSFER MODE. EVALUATION OF DETERIORATION CAUSED BY DEVICE

The experiments took place in a closed room, illuminated by ambient lighting (low photopic) and special test lighting the subject observed tests placed at a distance of 10 m in front of him. Several viewing configurations are possible depending on visual helmet configuration :

- bare head with binocular and right monocular vision,

- free left eye and TV image off for right eye which perceives landscape through the semi-reflecting prism. This corresponds to wearing the helmet with equipment turned off during daytime flying,

- identical situation except with left eye covered. This monocular perception permits evaluating the influence of optics alone on vision,

- left eye covered and operating TV image system : the right eye perceives a double image of landscape, a direct image and an artificial image,

- finally, the most restrictive situation where the right eye is stimulated by the TV image system alone. This is what happens in nighttime flying where the only image source is artificial.

All these configurations served as support for experiments on angular and stereoscopic acuity with, in addition, a reference for each subject, i.e. binocular vision, bare headed.

2.1.1. Angular acuity

Angular acuity was mesured using two types of black test objects displayed against a white background (luminance 82 cd.m-2), either Thibaudet's objects, a variant of Snellen's E for acuities above 2/10, or Foucault's sights for acuities of 0.5-2/10.

The test was first performed bare headed then under the four other typical conditions previously described.

2.1.1.1. Results

For all subjects visual acuity was above 12/10, bare headed, in binocular, or right monocular vision.

Vision through the semi reflecting prism alone did not impair angular acuity. It was always greater than 12/10. However, for the right eye vision through the camera and CRT was impaired. Strangely enough, acuity ranged between 0.8 and 3/10 (mean value 1.33/10). The origin of the nexpected dispersion has not found a definite explanation

Simultaneous right eye vision of the outside world and TV image by the right eye was also deteriorated but less since visual acuity is only 6/10. The synthetic image behaved as a noise source affecting direct vision through the prism. This is a significant effect. However, it is not of the same magnitude as the effect previously observed.

2.1.2. Depth perception

The experimental equipment was designed after Howard-Dolman's equipment. Three parallel grey bars were shown at a distance of 10 m from the subject. Each bar was viewed under an angle of 7' and the set of 3 bars represented 2' of arc. The subject did not perceive bar top or bottom. The two outside bars were fixed and served as reference ; the middle bar was moved by the experimenter, using an electric system. The subject was required to indicate whether he perceived the middle bar in front, behind or in the same plane as the other two bars. This was repeated for typical experimental situations. Respective bar position was determined for each angular display according to a threshold search technique in two stages :

First stage : constant stimuli, pseudo-random display : perception inversion thresholds were sorted out (in front/same and same/behind).

Second stage : pseudo-random displays centered on previously obtained thresholds made it possible to refine threshold assessment, interindividual variability being taken into account. The selecced measurement was the distance, in centimeters, between the front plane of the two reference bars and the test bar in the two above described procedures.

2.1.2.1. Results

Mean results are summarized in the following table, for all subjects. Numbers represent the distances in centimeters.

	BARE HEAD				EQUIPMENT OFF				EQUIPMENT ON	
	MONO R		BINO		MONO L		BINO		MONO R	
	THRESHOLD		THRESHOLD		THRESHOLD		THRESHOLD		THRESHOLD	
	Bk	Ft	Bk	Ft	Bk	Ft	Bk	Ft	Bk	Ft
MEAN FRONT/BACK DISTANCE	9	7	6,5	4,5	6	7,3	5	3,8	13,7	11,8
GENERAL MEAN	8		5,5		6,6		4,3		12,7	

Some remarks should be made

The used experimental device is not above critics, especially for the lighting of the bar system. There is a difference between front and back thresholds, associated with the experimental lighting device. This fixed lighting induced a change in middle bar luminance, depending on its position (10 cd.m-2 difference between extreme positions). This linear change was explicitely analyzed by some subjects ; others probably integrated it more intuitively into their response. An undesired learning process could therefore develop as test runs progressed. Threshold differences between mono- and binocular experiments diminished. Subjects used luminance fluctuations as a clue for bar position.

Comparison between monocular vision with equipment on and binocular vision with equipment off evidences a contour distinction threshold three time smaller for synthetic monocular vision. The quasi systematic advantage given to the threshold value for front of reference bars is also due to lighting conditions, associated with the contrast amplifying effect of the camera/tube system. It becomes harder for the subject to determine a "back" contour vision threshold.

Result restrictions turn this deterioration into an order of magnitude characteristic of used experimental conditions : head fixity, constant distance between eye and reference system, great contrast between bars and background, and, in addition, possibility for subjects to recreate reference points for reciprocal distances between bars.

We wanted to

- observe the effects of a dynamic image on reduced field TV on eye motility,

- test constancy of ocular synergy,

- show that simultaneous perception of two very different images is impossible but that, under given conditions, alternate viewing is possible,

- evaluate the possibility of reading symbology superimposed to a deteriorated image of the outside world.

For each one of these themes, we designed a test which implemented appropriate images, inducing eye movements recorded by electro-oculography.

2.2.1. Experimental protocol

2.2.1.1. Eye activity recording

The activity of each eye was recorded by electrooculography according to the method described by Angiboust and Cailler (8). This method was selected because of its relative implementation simplicity, of the few constraints imposed upon subjects, and of its compatibility with wearing display equipped helmets.

The horizontal motion component with time and amplitude indications is recorded on a tracing table, together with data generated by the gyrometric sensors of the helmet-mounted display.

Therefore, both head and eye movements appear on the same recording.

We selected not to authorize vision of the outside world (experiment room) through the prism and to use the system's technical capabilities to create a background close to operational reality, controlled and identical for all subjects. To do this, landscapes were filmed on video tape during low altitude (60 m), very low altitude (15 m) flight at a speed of approximately 150 km/h, above woods and fields, following skirts of forests. Significant changes during stationary or dynamic flight were also recorded.

2.2.2.1. Experimental procedure

The subject sat in a helicopter seat, with electrodes placed on either side of each eye in the median horizontal plane. For calibration, the subject alternatively fixed his gaze on two points distant by 40° according to two procedures used as reference : binocular vision (natural condition), monocular vision with left eye covered.

2.2.2. Effect of background images on eye mobility

As could be expected, an optokinetic nystagmus was observed during the display of flowing forest skirt images. The subject was instructed to read these images as during real flight. The two classical nystagmus phases were observed : landscape follow-up for 0.5-2s in the direction of image flow.
Amplitude fluctuation was approximately 3-15°. Rapid return phase consisting in eye repositioning in the direction opposite to landscape flow. The amplitude was 2-10° for less than 1/10th of a second.

2.2.3. Eye synergy

Eye synergy evidences relationships between eye movements of both eyes when only the right eye is continuously tracking the image. A circular sight generated by stroke scanning appears at the center of the screen with a diameter is 2° and a thickness of 6'. The sight has a horizontal trajectory at the center of the screen ; its motion, at constant speed (8°.s-1) is alternative and its amplitude is 5, 10, 15 and 20° from screen center. The cycle lasts 30 s and is repeated 3 times. The subject is instructed to follow sight motion carefully with the right eye. The left eye is covered as well as the outside prism wall. The image background is the very low altitude flight recording. The subject must press on tongs whenever sight direction changes. These signals are plotted.

2.2.3.1. Results

The right eye carefully follows sight motion. As tests are repeated, a learning process appears with anticipation of sight motion. Binocular behavior is such as could be expected, i.e. both eye movements slow down when sight direction changes.

During visual tracking gyrometers record some horizontal and vertical helmet movements. Horizontal movements are recorded for all subjects. Their velocity does not exceed 10°.s-1 and they last approximately 0.5 s. Such movements usually occur after trajectory inversion and when this change is indicated by the subject, therefore when the eye shifts in the opposite direction.

In most cases, it is not an isolated motion but rather a sequence of alternative motions of decreasing amplitude. The initial movement probably corresponds to a reflex of tracking activity ; however, following motions may be due to helmet inertia.

For certain subjects, it was also observed that the fact of pressing on the tongs triggered a reflex contraction throughout the entire body. This contraction was directly recorded by gyrometers, although it was not directly related to visual behavior. In this case, movements were essentially vertical, lasted 0.5-1 s, at a velocity less than 5°.s-1.

For head motions, we can conclude that outside of the general activity condition, vertical head motions are unfrequent and their velocity is low. Horizontal head motions are more numerous. However, their low amplitude does not allow them to be given a role in visual information pickup.

Subjects were asked to observe, in priority, the background image while detecting changes in sight direction. The subject is, in this case, freer to select his eye strategy since he is asked to view the recorded flight image as he would if he was flying his aircraft. Subjects have a rather small eye activity with saccadic fixation movements of approximately 10° amplitude.

Both eyes have totally symmetrical behaviors. Head motions, mostly horizontal, are more numerous and usually last for some time. This makes them different from the previous situation where they were short and more rare. Vertical motions were practically non existing.

The manual direction change indication task performed by the subject is less accurate in this experimental context. Anticipated responses or lack of response are more frequent than during priority sight tracking.

2.2.4. Inter-ocular rivalry

The subject is placed in a situation which tends to create marked binocular rivalry. Right eye stimulation is identical to first stimulation, i.e. green monochromous image (80 cd.m-2) with continuous tracking task and far vision requiring no accommodation.

A meter is placed in low position at 30 cm from the ground and 1 m from the left eye (10° from the axis). Its digits are lit and indicate time in seconds. Signal is emitted in orange at a luminance of 21 cd.m-2. This meter represents for the subject an instrument of the flight panel. The room is made dark. The subject performs a double task : follow the sight (first task) and report the appearance on the meter of second numbers ending with 0 or 5. Meter checking is left to subject's initiative. He must only press on the tongs whenever he sees a 0 or a 5.

The two images respectively perceived by the two eyes have different luminances, wavelength, contours and task support. There is a certain parallelism between this situation and those encountered during real flight with information source sharing between helmet-mounted display and instrument panel.

2.2.4.1. Results

Sight tracking :

The sight is properly tracked by continuous eye movements. However, the amplitude is reduced compared to interocular synergy experiment (2.2.3.). Similarly, an interval of a few degrees is sometimes observed between eye and sight. Changes in tracking direction are much smaller.

Meter reading :

The counting strategy is left to subject's initiative. Some subjects used their intuition of time, others organized their strategy by counting. The result is either an observation every 5 seconds or successive observations at a frequency of 1-3 per 5 seconds. Depending on subjects, fixations last 0.3-1 s. Longer times are observed in subjects who prefer waiting a few tenths of a second until 0 or 5 appears. Reading intervals were satisfactory for all subjects, whatever strategy was used.

Subjects were instructed to keep their head upright, as much as possible, such as the operational situation required it (thermal camera outside the aircraft responding to helmet motions).

Horizontal head motions never occured for some subjects, were very light for others although meter reading required a 30° gaze shift down, up to 30° to the left (10° shift from axis and 20° excursion).

Eye synergy :

When the right eye is dominant because it must follow sight motion, the right eye only moves 31° and the left eye 28° when the sight travels 40°. Left eye trajectory is then 10 % shorter than right eye trajectory.

When the left eye is dominant (meter reading), the theoretical shift is always 40°. In fact, left eye moves by 42° whereas right eye moves by only 32°. The difference between left and right eye shift is 25 %. This difference in percentage is correlated with the type of task performed ; in one case tracking task in the other accurate reading. Systematically, the amplitude of the trajectory of the eye which is not addressed by the task is lower than that of the eye required to pick-up priority information.

Most subjects reported feeling that the non observed image was neutralized to the advantage of the other image. None of the subjects reported experiencing superimposition or fusion of the two images displayed under the described experimental conditions. These results confirm that two very different information sources cannot be simultaneously perceived by both eyes. In addition, alternate reading probably implements complex and unusual mechanisms which must be used very cautiously.

2.2.5. Coherence rivalry between monocular data

The helmet-mounted display is a device which was developed in order to show pilots an unusual image. They have to observe the outside world through an electronic device (LLTV or FLIR) under reduced visual field with superimposed synthetic data (digital). The total image is a virtual image displayed at the infinite.

"How is such information perceived by pilots ?" is the question which we are trying to answer in this experiment. There is indeed a double monocular task : perception of a landscape image and of a synthetic image in paracentral vision.

Eight letters were successively displayed at screen periphery in the following order :

L A F
U   Z
P T I

The display cycle is constant : L.I.A.U.Z.T.P.F.

The subject is instructed to watch screen center and read the letter as soon as it appears, to name this letter and return to the center.

The appearance frequency is controlled by the experimenter for three cycle repetitions : the first and last are slow, every 2-3 seconds, the second is faster approximately every second.

Letter appearance on the screen is graphically recorded in order to measure response time elapsed until eye motion takes place. This experiment has two perspectives :

- observation of eye motions when stimulation is unique under conditions of eye activity such as punctual research, different from previous experiment which only concerned continuous observation,

- letters on vertical edges appear at an angle of $\pm$ 20°. It is interesting to observe whether reading these letters cause reflex head motion attempting to bring visual and head frontal axes closer. This reflex is usually observed as soon as target is at more than 15° from visual axis.

2.2.5.1. Results

When the first letter cycle is displayed, mean time interval before saccade begins is, depending upon subjects, 0.3-0.5 s although 2-3 second intervals are not unfrequent. Fixation time for reading is approximately 0.5 s.

For following cycles, which are repeats with the same letters in the same order, a learning process appears, characterized by anticipation of eye positioning and shorter response times. Fixation time is approximately 0.3 s. False anticipations are also observed, especially when letter succession is slower, i.e. every 3 s.

For all subjects, both eyes have symetrical compartments for the repetitions as far as amplitude, velocity and shape of eye shifts. Subjects did not report any special discomfort when reading letter sequences.

Head motions only occur during rapid eye movements. Vertical head motions occur at a velocity of approximately 10°.s-1 over an average time of 0.5 s. Horizontal motions occur at only 5°.s-1 but over longer times, 1.5 s.

The reflex nature of this activity is evidenced through the quasi general decrease in head movements as subject performs his repetitions.

2.3. INTERVIEWS WITH SUBJECTS

After each experiment, subjects'impressions were recorded on semi-open questionnaires. Only the most striking are recorded.

2.3.1. Experiments on rivalry types

For the following experiments, less different from flight circumstances, opinions were more numerous.

The sight was systematically perceived in a plane closer to the subject than that of the recorded image. No optical cause can induce an objective gap. The origin of this phenomenon is psychophysiological. Two channels should be explored : image quality and cognitive nature.

Contrasts exist between the components of the image displayed here : luminance contrast, definition contrast, cognitive contrast.

Luminance contrast : in order that symbology be easily differentiated from filmed landscape, luminance had to be greater. Luminance differences are a common factor in the appreciation of subjects' relative position.

The definition of the recorded background image is much lower than that of the sight. A "definition contrast occurs" whose influence on perception has already been illustrated during studies on target detection and image analysis according to image structuration level.

There was no formal or design relationship between symbol and background image. This is illustrated by the difficulty felt by subjects when trying to observe both simultaneously.

It did not seem possible to simultaneously follow sight motion and flowing by landscape. When priority is given to sight tracking, subject perceives changes in landscape surface but cannot describe details which appeared on the image. If priority is given to landscape viewing, detection of sight motions is less accurate.

An alternative observation could be made according to the opinion of some subjects. This would call for other experimental situations since it should be reminded that what we used here was a sight without any symbolic or dynamic relationship with the background image.

Sight tracking sometimes causes an illusion. When sight trajectory and landscape motion were opposed or cuncurrent, the subject could not exactly distinguish the resulting relative motion. As a result, the subject gave a false response or no response.

2.3.2. Alternative consultation

Alternative reading of meter and recorded image showed generalized neutralization of the unread image since none of the subjects perceived the two fused or even superimposed images.

Some subjects reported remanence of sight image during meter reading. This is a physiological phenomenon which has no direct relationship with binocular vision such as is considered here.

Some subjects also reported that shift from meter reading to sight tracking is easier than the shift in the reverse order.

3. INFLIGHT EXPERIMENTS

A laboratory evaluation showed deterioration of the perception of a subject wearing a helmet-mounted display. However, real flight involves many more factors. It is therefore necessary to study the behavior of a pilot flying a helicopter with, as sole source of visual information, the image of the associated video sensor. However, helicopter flying imposes light measuring instrumentation and makes strict renewal of experimental measurements difficult. The emphasis was therefore laid upon situations which were easy to create and which allowed :

- assessment of visual acuity and depth perception decrement during various types of flight,
- comparison between the various configurations of vision possible while wearing a helmet-mounted display,
- permanent observation of h .-mounted display/pilot interactions evidencing phenomena which are characteristic of this situation.

3.1. STUDIED FUNCTIONS

Three important functions for low altitude flight were retained as representative criteria : pilot's evaluation of altitude, of distance between him and obstacles and of the velocity of his motion.

3.1.1. Evaluation of flight altitude

Several parameters were judged to be relevant and were studied in various experiments during two types of flight translation :

- two velocities : 60 or 90 kts,
- over open fields or following forest skirts,
- altitudes ranging between 3 and 30 m, i.e. approx. 10-100 feet,

stationary flight : in front of an edge or over a special area marked "H".

These measurements are made in two contexts :

- active equipped pilot : pilot wearing helmet-mounted display must bring his aircraft to a prescribed altitude and maintain it during stabilized flight. Reading the radiosonde permits comparing prescribed altitude with subject's response,

While wearing a helmet-mounted display, the pilot cannot read the instrument panel, and particularly the radiosonde. He can therefore only trust his sensations. Moreover, since he gets no clue on the quality of his response, the pilot cannot correct his judgment. The succession of proposed or required altitudes is random.

Flying over landscapes such as fields or forest skirts allows pilots to keep using their usual clues. They are indeed trained for very low altitude flight where field and forest skirt size and texture are information clues.

3.1.2. Distance evaluation

Distance is measured during translation flight using various objects such as posts, forest skirts, vehicles, houses. The pilot is asked without warning, to give a very rapid evaluation of distance separating him from a given obstacle. However, since no distance measuring device is mounted on the test helicopter, it is impossible to make an objective comparison between pilot's evaluation and real distance.

The security pilot is the reference ; his great practice of firing tests and obstacle avoidance provides him with a great experience of visual assessment of distances.

3.1.3. Evaluation of motion velocity

The evaluation of motion velocity rests upon the optical quality of the video display and upon the analysis of perceptual clues extracted from the reduced visual field. The subject is asked to evaluate the translation speed during stabilized flights. The airspeed indicator is the objective reference. Its location makes it invisible for the pilot subject. No clue is provided on response quality.

3.2. INFLIGHT TESTING

3.2.1. Subjects

Subjects were four test pilots between 34 and 44 years of age, with 2,000 - 5,500 flight hours.

They participated in laboratory experiments.

In order to make subjects familiar with the investigated equipment, each subject flew four training flights. This learning phase was left to each pilot's own rhythm. The idea was to bring them to fly safely, as identically as possible to tactical flight. It should be noted that none of the tasks required during experiments *per se* was mentionned during training, in order to avoid any facilitation process.

3.2.2. Experimental equipment

An ALOUETTE III helicopter was used for in-flight tests. A safety pilot attends all tests in order to take control in case of human or technical failure. He makes sure that the flight is normal and provides aircraft environment control. He flies the aircraft when the subject is passive and brings it to the altitudes selected by the experimenter on board. Finally, he is the reference for certain evaluations.

3.3. RESULTS

The experiment included two flights of approximately one hour for three of the four pilots and a single flight for the fourth pilot. Weather and technical conditions, and experimental times did not permit using the same successive order of various types of flights for all pilots, nor to collect the same amount of data from all pilots.

It was therefore not possible to process observations using statistic techniques ; only trends are indicated, represented by dot clouds which permit comparing orders with subjects'responses.

3.3.1. Altitudes in feet

Estimates were presented for all subjects in three contexts :

- at 60 knots over forest skirts,
- at 60 knots over open fields,
- at 90 knots over open fields.

Strict comparison between the answer provided by the subject and the indication of the radiosonde in order to indicate a rate of errors is not possible. The subject gives a rough appreciation of the altitude : the answer "40 feet" can actually be given for altitudes between 36 and 43 feet. This range is different for different pilots and at different altitudes. The radiosonde dial can be read with plus or minus two feet. Any accurate quantification of the error would therefore be false. Such results should thus be merely considered as trends.

3.3.1.1. Flight over forest skirts at 60 knots (Fig.2)

It is obvious that active subjects bring their aircraft at a higher altitude than prescribed. They overestimate. Inversely, passive subjects bring their aircraft to a lower altitude than requested. They underestimate.

3.3.1.2. Flight over fields at 60 knots (Fig. 3)

The same distinction can be made between active and passive subjects. However, response dispersion is different. Active subjects overestimate the altitude, but their responses can be, in some cases, as much as triple the real value. Passive subjects mostly underestimate the altitude ; the maximum spread is independent of the prescribed altitude.

3.3.1.3. Flight over fields at 90 knots (Fig. 4)

Conditions are practically the same as for the 60 knot speed. Altitude is greatly overestimated and underestimated with greater spreads for the first tendency and results are more accurate for the second. The 50° speed increase does not seem to notably worsen or improve altitude evaluation.

3.3.1.4. Stationary flight over landing area (Fig. 5)

Responses are rather accurate up to 40 feet above the ground. Beyond that point, active pilot's overestimation is variable. The small number of observations made on passive pilots does not allow clear tendencies to be evidenced beyond 40 feed.

3.3.1.5. Stationary flight in front of a forest skirt (Fig. 6)

The forest skirt was the same for all tests. Tree tops were, as an average, 30 feet from the ground. Very low altitude flight training permitted the subject pilots to give a rather accurate evaluation of their altitude compared to a forest skirt whose main branches and tree top altitude for various tree species was known to them. In fact, evaluations are more accurate than in previous situations and the active/passive dichotomy fades out. The role of a know reference is most significant.

Such accurate evaluations during stationary flight contrast with those obtained during translation flight although the reference object, a forest skirt, was used.

3.3.2. Distances in meters (Fig. 7)

The reference value is the quantification made be the non equipped pilot trained for this type of evaluation. The response is that provided by the pilot wearing a helmet-mounted display in an active situation.

Responses are very accurate for distances under 100 m for known objects. The few measurements of distant objects are overestimations sometimes as high as 100 %.

These results on distance evaluation should be compared to those of previous studies. GIBSON and BERGMAN (04) showed that in passive situations pilot students always underestimated distances, even with binocular vision. In active situations GROSSLIGHT et al. observed overestimation with monocular vision and underestimation with binocular vision during wheel centering on target. Compared to this last study, our pilots with monocular vision correctly evaluated short distances (under 100 m) and alike GROSSLIGHT's subjects only overestimated for great distances. If we consider results obtained by GIBSON on pilot students, our pilots can be considered as being, partly. in a training situation. They are active and give different responses. If we review results of all three types of studies carried out in very different contexts but with the same finality, it can be concluded that very complex phenomena are involved. It does seem to be a phenomenon of cortical integration.

Finally, considering that these experiments were performed during day-time in a clearly photopic environment, it seems difficult to relate them to observations made on the poor appreciation of distances during night flight.

3.3.3. Motion velocity (Fig. 8)

The pilot is periodically invited to evaluate speed, between altitudes of 20 and 100 feet without systematization.

Estimates are generally accurate. However, some overestimations are made when speed increases.

3.3.4. Visual acuity test

We felt that it would be interesting to test the separating power of the equipped eye in the real environment. After each flight, an angular visual acuity test was performed using Landolt rings.

The helicopter was landed and the rotor in motion. Under such conditions, acuity averages 2/10 MONNOYER. This value is slightly higher than that observed in the laboratory. The higher luminance of the test performed in the open probably explains this improvement.

3.4. OBSERVATIONS MADE ON TEST FLIGHTS

Information regarding learning of the helmet-mounted display use was gathered from pilots flying with this equipement for the first time. These pilots reported stresses felt during flight and maneuvers.

In illusory sensation was also reported in a special visual configuration using the helmet-mounted display.

3.4.1. Learning

The four preliminary flights performed by all pilot subjects were, for each one of them, the first time they wore a helmet-mounted display in flight, characterized by restricted visual field (30° x 40°) and non negligible restriction of the eye's separating power (2/10).

Pilots learn very quickly to fly with a helmet-mounted display. The most dramatic learning process occured during the first flight.

The level of performance reached after four flights was quite satisfactory since it authorized low altitude flights (15 m). Learning was also evidenced by the possiblity of flying longer and longer flights as more repetitions were made with reduced fatigue. Pilots describe their progress in terms of fewer head motions, greater maneuver comfort in configurations more similar to natural binocular flight.

This phase could not be subject to a systematic study in order to observe and quantify progress and strategies for the different pilots. This remains to be done. No generalization should be done. Subjects are all test pilots and therefore used to adapt quickly to a special flight device. A less specialized population could encounter other problems.

3.4.2. Flight stress

A short interview with each pilot at the end of the experiment permits identifying maneuvers which are made more difficult, maybe even impossible with the helmet-mounted display :

- rapid landing and take-off, obstacle contour, very low altitude flight (lower than 30 feet), sharp right and left turns are more difficult,

- turns with more than 45° slope, quick stop on obstacle and landing on a precise not marked point seem to be practically impossible.

Rapid stop and landing without reference imply sharp evaluation of distances and magnitudes and we saw to what expent the provided image impaired this perception.

3.4.3. Illusions

At the end of each flight the pilot was placed in a binocular situation with operating helmet-mounted display image and an attenuating filter over the left eye. The filter was selected in order to attenuate difference in the luminance between both eyes.

The pilot, with binocular vision in reduced field (30° x 40° for each eye) viewed an artificial image with the right eye and a natural image with the left eye.

As soon as this system was arranged, pilots expressed a very comportable feeling (after 45 mn of monocular flight). A low altitude flight over a wheat field was no problem but the pilot misevaluated his altitude : he believed he was flying 5 m over the field although he was flying just 1-2 m over the ears at 80-90 knots.

Landing on a known landing area, a pilot thought he was 3 m high when the wheels touched the ground. This misevaluation was so obvious that the pilot discarded the information provided by the ground effect, ascribing it to a change in wind direction.

Such misinterpretation of information is typical of illusory sensations. The binocular configuration induced great overestimation of the depth in all four pilots under similar circumstances. This misperception was much greater than simple overestimation which had never caused such great discrepancies between perception and reality for such low altitudes.

3.4.3.1. Hypotheses on observed illusion

In order to explain this illusion, PULFRICH's stereophenomenon described in 1923, contrasts and spatial frequencis mentionned by BLACK and CORNACK (02), disparity in retinal image sizes (FOLEY et al. (03)) can be evoked.

Pilots were observing the world through two images whose difference in light level was in a ratio of approximately 20 (equipped right eye/left eye with neutral filter). This is the base of PULFRICH's stereophenomenon.

Image contrasts are different for right and left eye ; in fact contrast range available on TV is smaller than that observed for the left eye (direct vision of outside world). In addition, spatial frequencies perceived by both eyes are different : right eye is handicapped compared to left eye.

Finally, if we consider that the scale 1/1 through the optical device was obtained only for distances of more than 10 m, for shorter distances disparity in image size between both eyes can also be observed. Flight altitudes were lower than 10 m when illusions were observed.

3.4.3.2. Synthesis on hypotheses

As a conclusion, each of the quoted disparity sources could be the cause of a depth illusion in a special context. All these disparities occur when the pilot is wearing a helmet-mounted display in binocular vision. Some differences should be noted : experiments use mobiles which move along an axis perpendicular to gaze, whereas the helicopter creates image motion parallel to gaze, therefore an image moving up and down mostly composed of horizontal lines. Experiments, on the contrary, use mostly vertical lines. Hypotheses formulated by the various authors rest upon parameters, motion axis, orientation, contrasts, whose real effects are poorly known.

In such a context, it is not possible to selectively ascribe the observed illusion to a given factor. It is rather caused by an intricate combination of all factors.

CONCLUSION

The evaluation performed here tested a mockup representative, by its general architecture, of devices designed for helicopter tactical night flight.

The most important conclusion is that pilots were able to fly using this device. However, some maneuvers were impaired. The cost, in terms of extra workload, was not directly evaluated. Clinical observations and description of simple phenomena reveal that it is far from being negligible. It is difficult to alleviate this workload since its underlying mechanisms are poorly known.

Some performance degradations are caused by the technical state of the art of the equipement. They can be suppressed by chosing other experimental protocols for other experiments. The effect of reduced visual field has already been studied inflight without using this equipment (PAPIN et al. (10)).

Other stresses are inherent to the design of the device. Thus the difficulty to locate oneself in space. Special solutions must already be investigated.

The main idea is to provide the pilot with additional information to supplement information no longer available. This is the aim of studies referred to by the general name of symbology (PAPIN (09), SANTUCCI (11)).

Thus, because of its joint laboratory/field aspect, this study identified major problems which will require technological developments and studies focused on human factors.

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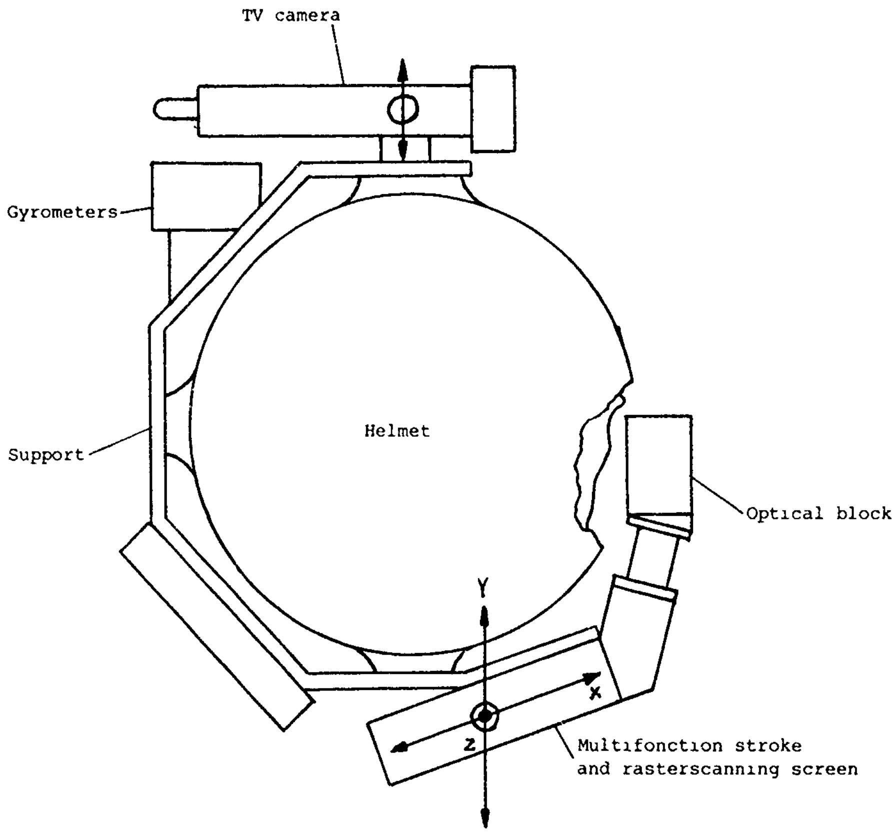


FIGURE 1 : DIAGRAM OF "HELMET MOUNTED DISPLAY"

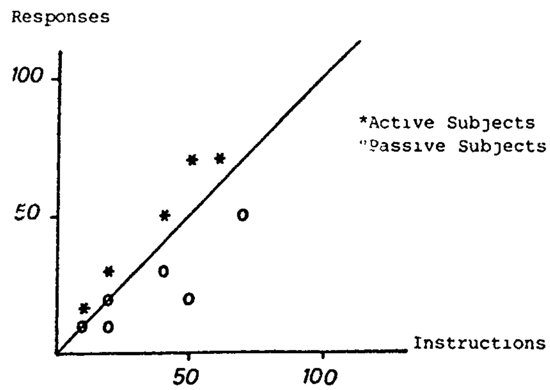


FIGURE 2 : ESTIMATION OF ALTITUDE IN FEET
AT 60 KTS OVER FOREST SKIRTS

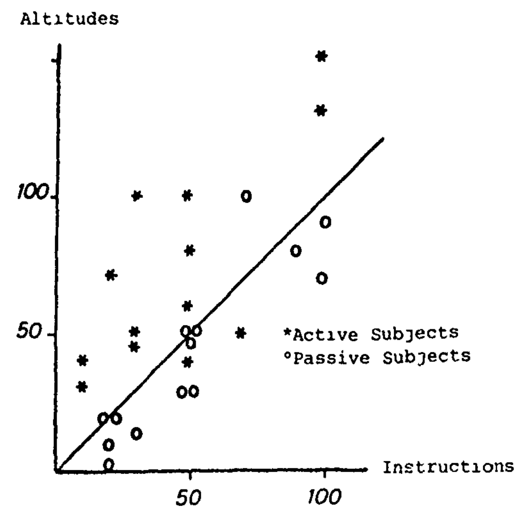


FIGURE 3 : ESTIMATION OF ALTITUDE IN FEET AT 60 KTS OVER FIELDS

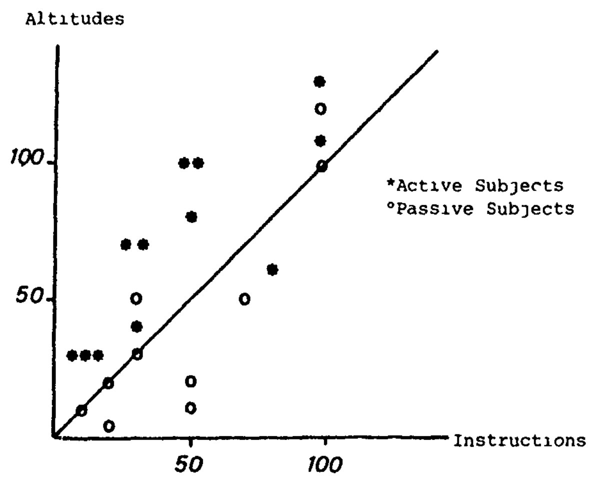


FIGURE 4 : ESTIMATION OF ALTITUDE IN FEET AT 90 KTS OVER FIELDS

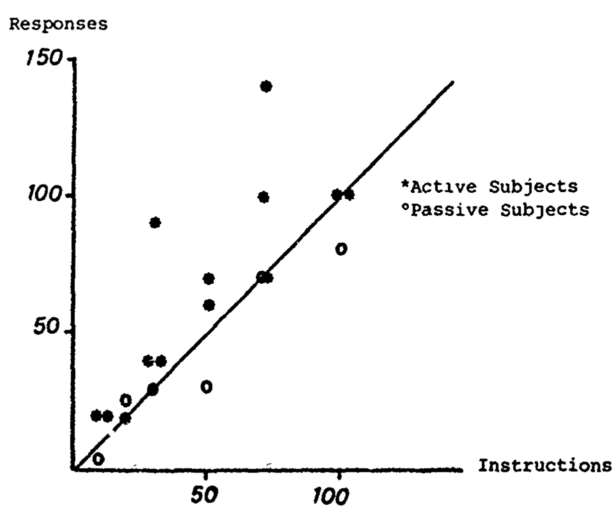


FIGURE 5 : STATIONNARY FLIGHT OVER LANDING AREA

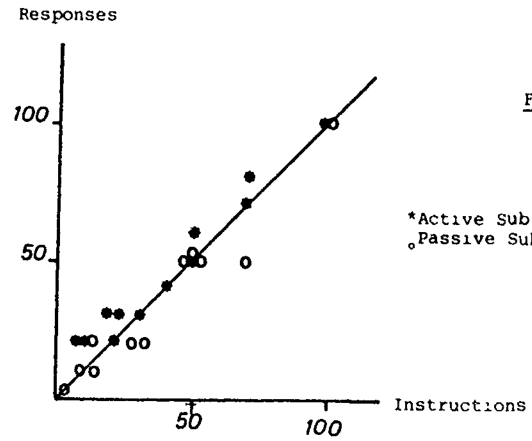
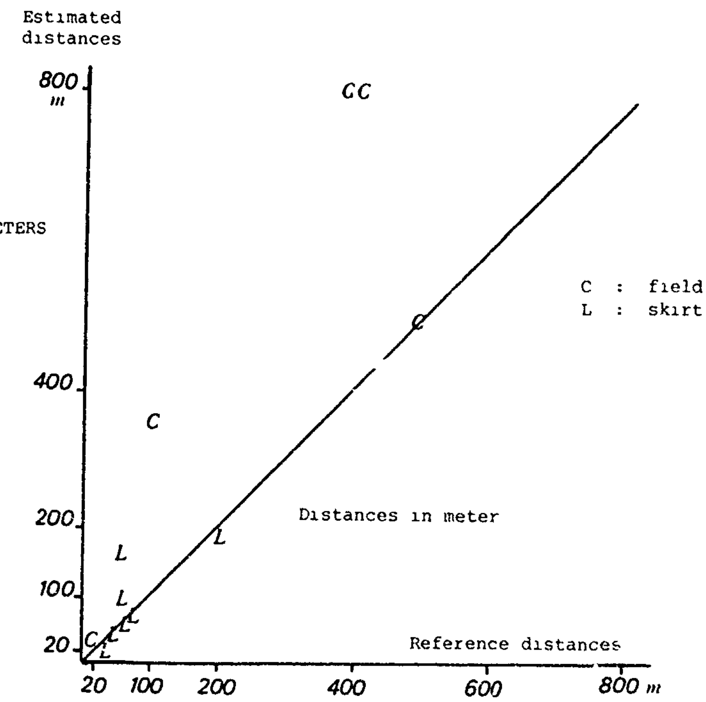


FIGURE 6 : STATIONARY FLIGHT IN FRONT OF A FOREST SKIRT

FIGURE 7 : ESTIMATION OF DISTANCES IN METERS



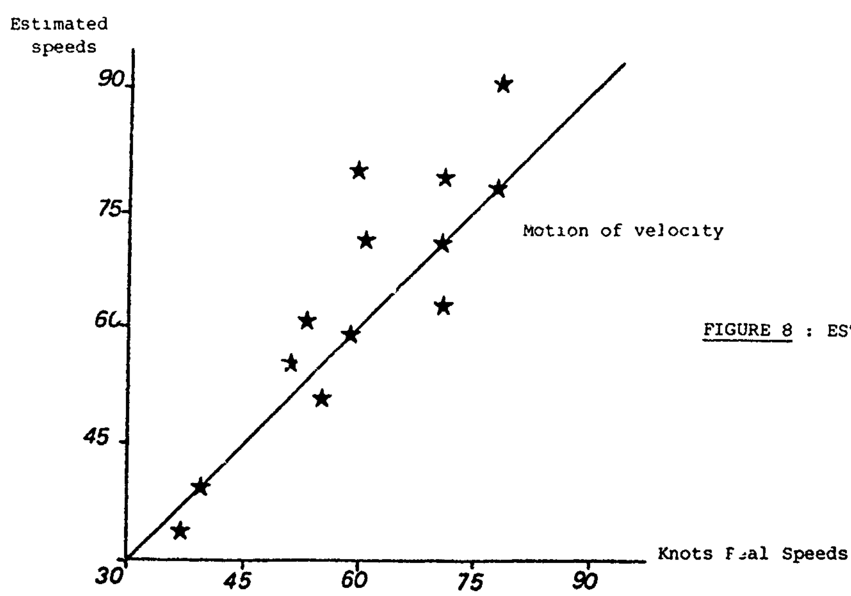


FIGURE 8 : ESTIMATION OF MOTION VELOCITY

EVALUATION D'UNE MAQUETTE DE VISUEL

POUR HELICOPTERE

Médecin en Chef SANTUCCI Guy
Professeur agrégé de Physiologie et d'Ergonomie Aérospatiales

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RESUME

Dans le cadre d'un projet de visualisation F.L.I.R. montée sur "visuel de casque", une étude psychophysiologique a été réalisée avec une maquette. Ce travail comportait une phase en laboratoire et une en vol.

En laboratoire :

Les expérimentations ont porté sur l'acuité visuelle angulaire, le sens du relief et l'acuité stéréoscopique d'une part, et d'autre part, à l'aide de l'électro-oculographie sur le comportement binoculaire en stimulation monoculaire pour : la synergie inter-oculaire, la rivalité binoculaire, le nystagmus optocinétique.

Les résultats ont montré une perte des acuités angulaires et stéréoscopiques et ont permis de préciser les composants de l'activité oculaire dans cette situation.

En vol :

Des contraintes sur l'activité perceptive lors du vol à basse altitude en hélicoptère ont pu être constatées, toutes deux variables selon la valeur considérée :

- surestimation des distances et altitudes pour le pilote actif,
- sous-estimation chez les pilotes passifs,

Une illusion sensorielle a été constatee dans certaines utilisations binoculaires du "visuel de casque". Elle concerne la vision du relief. Des hypothèses sont avancées pour ces différentes altérations sensorielles.

INTRODUCTION

L'évolution des strategies et des tactiques militaires conduit à multiplier les opérations nocturnes. L'utilisation de l'hélicoptère dans ses différents emplois n'échappe pas à cette règle. Les fonctions visuelles de l'homme en vision nocturne n'autorisent pas des vols tactiques en toute sécurité. Des technologies de suppléance (MENU et Coll. (08)) ont donc été développées. Parmi celles-ci, l'imagerie thermique occupe un place de choix. Elle repose sur l'utilisation d'un capteur et d'une chaîne électronique qui transforment le rayonnement infra-rouge en émissions visibles par l'oeil humain.

La génération de cette émission est faite par un tube cathodique qui, au tout début, était fixé sur la planche de bord. La caméra thermique avec un champ réduit devait donc être mobile pour explorer l'espace environnant. Initialement, sa direction de visée était commandée manuellement, ce qui se traduisait pour le pilote par l'observation de l'espace latéral.

Il n'y avait donc pas asservissement de la caméra à la direction du regard. Pour pallier à ces inconvénients est né le concept de "visuel de casque". Il s'agit de présenter toujours devant l'oeil le paysage qui se trouve dans l'axe de la tête...

La caméra thermique, située pour des raisons propres à l'extérieur de l'aeronef, est asservie aux mouvements de tête. Son image, après traitement, est présentée sur une visualisation fixée sur le casque du pilote.

L'état des technologies et de leurs coûts ont incité les ingénieurs à n'installer dans un premier temps qu'une seule visualisation en face d'un seul oeil. Les conséquences sur la perception visuelle et sur le pilotage se devaient d'être étudiées. Pour cela, une maquette simulant cette situation a été mise à notre disposition. Elle a permis de réaliser l'évaluation présentée ici.

1. LE VISUEL DE CASQUE

1.1. DESCRIPTION TECHNIQUE

L'équipement étudié dénommé "Visuel de casque" est la maquette d'un système de présentation optique d'informations intégré à un casque (figure 1). Il est composé d'un casque de vol où sont fixés :

- une caméra TV de petite taille,
- un tube télévision multimode relié à la caméra pour le balayage TV et à une électronique de pilotage pour le balayage cavalier. L'émission est monochrome verte pour les deux types de balayage,
- un bloc optique comportant un prisme semi-réfléchissant assure la présentation de l'image TV collimatée à l'infini devant l'oeil droit du pilote. Le champ visuel est de 30° x 40°. Le prisme permet la superposition optique de l'image synthétique à celle du monde extérieur. Cependant, la superposition de l'image télévision et celle du monde extérieur ne peut être obtenue que pour des objets situés au moins à 10 m (ceci est dû à la parallaxe entre la caméra et l'oeil droit).

Divers dispositifs de réglage assurent la compatibilité de l'équipement avec la variabilité morphologique des personnes amenées à le porter.

1.2. CARACTERISTIQUES PHYSIQUES DE LA STIMULATION

En vision naturelle, les deux yeux reçoivent chacun une stimulation similaire en forme, niveau de lumière, couleur, mouvement ; il n'en est plus de même avec le port du visuel de casque.

Ses particularités peuvent être regroupées en deux grandes familles :

1.2.1. DES STIMULATIONS DIFFERENTES POUR L'OEIL GAUCHE ET POUR L'OEIL DROIT

1.2.1.1. La luminance stimulant l'oeil droit ne peut varier que de 30 à 150 cd m-2, alors que l'oeil gauche peut être soumis à une gamme de luminances beaucoup plus vaste, celle du monde naturel.

1.2.1.2. L'oeil droit reçoit :

- une image télévision (625 lignes) monochrome verte. Il s'agit d'une stimulation intermittente dans le temps et dans l'espace,
- la définition de l'image est moins bonne (nombre de points et gamme de contrastes réduits par rapport à la réalité),
- cette image est virtuelle et toujours collimatée à l'infini quelle que soit la distance de l'objet.

Ceci souligne les différences avec la stimulation reçue par l'oeil gauche qui est une vue directe du monde exterieur.

1.2.1.3. Des situations monoculaires ou binoculaires ou d'un troisième type

L'architecture de la maquette autorise un certain nombre de situations dont certaines sont pour le moins inhabituelles avec des conséquences plus ou moins prévisibles. Seules ont été effectivement évaluées celles correspondant à des situations pertinentes d'utilisation du dispositif.

En monoculaire, oeil gauche occlus, seul l'oeil droit est stimulé par l'image du tube télévision sans vision directe du monde extérieur. La perception du relief ne peut se faire par mise en jeu de la stéréoscopie ; seuls les facteurs corticaux de cette perception sont utilisés et ceci sur une image dégradée.

En binoculaire : l'oeil gauche voit le monde extérieur de façon naturelle ou à travers un filtre neutre atténuateur, la polychromie est conservée de même que la gamme des contrastes. Ce filtre est utilisé lorsque la différence prévisible de luminance entre les deux yeux est excessive.

Le canal visuel droit est dans une situation tout à fait inhabituelle. En effet, il reçoit une image prise par un capteur situé à gauche de l'oeil gauche.

Le troisième type mérite le terme de bi-ocularité plutôt que de binocularité au sens traditionnel du mot.

Devant une telle situation : monocularité avec image artificielle, fausse binocularité, les données de la bibliographie ne répondent pas pleinement à la question qui se pose : "Peut-on piloter un hélicoptère en conditions opérationnelles avec ce dispositif ?".

Les quelques données disponibles permettent d'établir un cadre pour l'expérimentation et mettent en exergue les points cruciaux dont l'influence doit être vérifiée. Ainsi LEGRAND (07) montre bien le rôle dans la perception du relief de l'acuité visuelle, de la disparité des images rétiniennes qui doivent rester cohérentes. Parmi tous les facteurs cités par LAYCOCK (06) intervenant dans la rivalité binoculaire, certains sont mis en jeu par le "visuel de casque" : la différence de luminance, la différence de complexité des deux images, ainsi que les mécanismes accommodatifs. Tous ces facteurs sont liés au fait qu'il est considéré que les centres de commande sont identiques pour les deux yeux. A cela, il convient d'ajouter la prise en compte des problèmes cognitifs apparaissant lors de l'utilisation opérationnelle de ces dispositifs : traitement d'informations plus ou moins complexes, de natures variées.

On remarque que les approches les plus fréquentes sont basées soit sur des travaux de laboratoire (physiologie fondamentale ou technologie pure) soit sur des études de terrain. Ces deux types de travaux sont rarement conduits par les mêmes équipes.

Conscients de l'intérêt d'une autre démarche, nous avons conçu le protocole d'évaluation de la maquette qui nous était confiée selon le schéma suivant :

- étude en laboratoire des fonctions visuelles pouvant être modifiées par le port d'un "visuel de casque",

- suivi par une étude en vol de certaines de ces fonctions et de leur intégration au sein des tâches aéronautiques.

Les dispositifs expérimentaux et le protocole ont été définis en fonction de cet objectif.

1.3. LES SUJETS

Pour ces deux étapes de l'étude, 15 sujets ont été retenus. Ils appartiennent tous au corps du personnel navigant civil et militaire et ont en commun d'appartenir à des organismes ayant une fonction d'essais. Leur âge est compris entre 29 et 48 ans. Ils ont effectué de 2000 à 5500 heures de vol. Leur appartenance au personnel navigant garantit un état satisfaisant de toutes les fonctions visuelles.

2. EXPERIENCES D'EVALUATION DU "VISUEL DE CASQUE" EN LABORATOIRE

Le "visuel de casque" était une maquette d'étude. Il convient donc d'établir une distinction entre :

- des observations tributaires des moyens employés. L'acuité du pilote en terme angulaire et stéréoscopique au centre et en bordure d'image est liée à la caméra et à l'optique utilisées,

- des observations tenant à la situation monoculaire et à la rivalité binoculaire, donc relativement indépendantes des précédentes, bien qu'il ne semble pas possible de disjoindre réellement acuité et rivalité binoculaires.

Enfin, l'ensemble de ces observations est également destiné à servir de référence en cas de comparaison avec d'autres chaînes d'affichage d'images (caméra TV + tube télévision) ou de présentations binoculaires ou bi-oculaires (image issue d'une même caméra présentée aux deux yeux simultanément).

2.1. EXPERIMENTATIONS LIEES AU MODE DE TRANFERT DE L'IMAGE REELLE.
EVALUATION DES DEGRADATIONS INDUITES PAR LE DISPOSITIF.

Description du site expérimental : pour ces travaux, un local clos est utilisé. L'éclairage y est fourni par deux sources : lumière ambiante (photopique bas), lumière propre aux tests utilisés.

Le sujet observe les tests placés à 10 m de lui. Plusieurs modalités de vision sont possibles selon la configuration visuelle du casque utilisé :

- tête nue en binoculaire et monoculaire droit,

- oeil gauche libre et chaîne image TV éteinte pour l'oeil droit qui perçoit donc le paysage à travers le prisme semi-réfléchissant. Ceci correspond au port du casque avec équipement éteint en vol diurne,

- situation identique à l'exception de l'oeil gauche occulté, cette perception monoculaire permettant d'évaluer l'influence de l'optique seule sur la vision,

- oeil gauche occulté et chaîne image TV en fonctionnement : l'oeil droit perçoit donc une double image du paysage : directe et artificielle,

- enfin, la situation la plus restrictive où l'oeil droit est stimulé par la seule chaîne image TV. C'est le cas d'un vol nocturne où la seule source d'image serait artificielle.
  L'ensemble de ces possibilités a servi de support aux expérimentations sur l'acuité angulaire et stéréoscopique avec en outre une référence pour chaque sujet constituée par la vision binoculaire tête nue.

2.1.1. ACUITE ANGULAIRE

Elle est mesurée au moyen de deux types d'otoptypes présentés en noir sur une plage blanche (luminance 82 cd m-2) ·

- soit ceux de THIBAUDET, une variante du E de SNELLEN, pour les acuités supérieures à 2/10e,
- soit des mires de FOUCAULT pour les acuités de 0,5 à 2/10e.

Le test est passé tout d'abord tête nue puis dans les quatre situations typiques précédemment décrites.

2.1.1.1. Résultats

Pour l'ensemble des sujets, l'acuité visuelle est supérieure à 12/10e, tête nue en vision binoculaire ou monoculaire oeil droit.

La vision à travers le prisme semi-réfléchissant seul n'altère pas l'acuité angulaire. Elle est toujours supérieure à 12/10e.

Par contre pour l'oeil droit, la vision à l'aide de la caméra et du tube cathodique est dégradée. Fait curieux, les acuités observées se situent selon les sujets entre 0,8/10e et 3/10e (la valeur moyenne est de 1,33/10e). L'origine de cette dispersion inattendue n'a pas trouvé d'explication certaine.

La vision simultanée par l'oeil droit du monde extérieur et de l'image télévision est également dégradée mais à un degré moindre puisque l'acuité visuelle n'est plus que de 6/10e. L'image synthétique se comporte comme une source de bruits parasitant la vision directe à travers le prisme. Cet effet est notable. Toutefois, il n'a pas l'ampleur de celui observé précédemment.

2.1.2. PERCEPTION DE LA PROFONDEUR

L'appareillage retenu pour cette expérimentation s'inspire de celui d'HOWARD-DOLMAN. On présente, à 10 m, trois barres verticales grises parallèles. Chaque barre est vue sous un angle de 7' et le système des trois occupe 2° d'arc. Le sujet ne perçoit de ces barres ni la base ni le sommet. Les deux barres latérales sont fixes et servent de référence. La barre centrale est mobile et déplacée à l'aide d'un système électrique par l'expérimentateur. Il est demandé au sujet d'indiquer s'il perçoit la barre centrale en avant, en arrière, ou sur le même plan que les deux autres, et ce pour les situations expérimentales typiques. La position respective des barres est déterminée pour chaque présentation angulaire selon une technique de recherche de seuil comportant deux phases :

Premier temps à stimuli constants par présentation d'ordre pseudo-aléatoire : les seuils d'inversion de perception sont dégrossis (avant / pareil et pareil / arrière).

Second temps : des présentations pseudo-aléatoires centrées sur les seuils obtenus auparavant permettaient de préciser ceux-ci rapidement compte tenu des variabilités inter-individuelles. La mesure retenue est la valeur en centimètre de la distance séparant le plan frontal des deux barres repère de celui de la barre test dans les deux procédures décrites ci-dessus.

2.1.2.1. Résultats

Les résultats moyens sont les suivants, exprimés en cm pour l'ensemble des sujets.

	TETE NUE				EQUIPEMENT ETEINT				EQUIPEMENT ALLUME	
	MONO D		BINO		MONO D		BINO		MONO D	
	SEUIL		SEUIL		SEUIL		SEUIL		SEUIL	
	AR	AV	AR	AV	AR	AV	AR	AV	AR	AV
Moyenne écart AV et AR	9	7	6,5	4,5	6	7,3	5	3,8	13,7	11,8
Moyenne générale	8		5,5		6,6		4,3		12,7	

Quelques observations doivent être formulées.

Le dispositif expérimental utilisé n'est pas exempt de toute critique, en particulier pour l'éclairage du système de barre. Il existe une différence entre les seuils avant et les seuils arrière qui est liée à l'éclairage du dispositif expérimental. Cet éclairage fixe induit une variation de la luminance de la barre centrale selon sa position (10 cd m-2 d'écart entre les positions extrêmes). Cette modification linéaire a été analysée explicitement par certains des sujets, d'autres l'ont sans doute intégrée à leur démarche de façon plus intuitive. Il y a donc eu possibilité d'un apprentissage parasite de la situation à mesure des répétitions. Aussi les différences de seuil entre monoculaire et binoculaire sont minorées. Les sujets utilisent les variations de luminance comme indice de position de la barre.

La comparaison entre la vision monoculaire équipement allumé et la vision binoculaire équipement éteint montre un seuil de distinction du relief trois fois moindre pour la vision monoculaire synthétique. L'avantage quasi systématique donné à la valeur de seuil pour l'avant des barres de référence est aussi issue des conditions d'éclairage et ce, joint à l'effet amplificateur de contraste de l'ensemble caméra tube. Il en résulte pour le sujet une plus grande difficulté à déterminer un seuil arrière de vision du relief.

Les restrictions apportées aux résultats font que cette dégradation est un ordre de grandeur propre aux conditions expérimentales utilisées comportant : immobilité de la tête, distance constante entre oeil et système de référence, contraste important entre barres et fond, avec, de plus, la possibilité pour le sujet de recréer des points de repère des distances réciproques des barres.

2.2. EXPERIMENTATIONS LIEES A LA VISION BINOCULAIRE

Rappelons que l'architecture du système est telle qu'elle stimule les yeux de façon différente ou un seul oeil de façon inhabituelle.

Nous avons voulu :

- observer les effets d'une image dynamique sur télévision à champ réduit sur la motilité oculaire,
- vérifier si la synergie oculaire demeurait bien constante,
- montrer que la perception simultanée de deux images très différentes est impossible mais que, sous certaines conditions, une consultation alternative est possible,
- évaluer les possibilités de lecture d'une symbologie surimposée à une image dégradée du monde extérieur.

Pour chacun de ces thèmes, nous avons conçu un test mettant en jeu des images appropriées, induisant des mouvements oculaires recueillis par électro-oculographie.

2.2.1. PROTOCOLE EXPERIMENTAL

2.2.1.1. Recueil de l'activité oculaire

Le recueil de l'activité de chacun des yeux sera effectué à l'aide de l'électro-oculographie selon la méthode décrite par ANGIBOUST et CAILLER (08). Elle a été retenue pour sa relative simplicité de mise en oeuvre, le peu de contraintes qu'elle fait subir aux sujets, et sa compatibilité avec le port du casque supportant l'équipement de visualisation.

La composante horizontale du déplacement avec indication de la durée et de l'amplitude est enregistrée sur une table traçante de même que les données issues des capteurs gyrométriques du "Visuel de casque".

Ainsi, sur le même enregistrement, sont disponibles les mouvements de tête et les mouvements des yeux.

Nous avons choisi de ne pas autoriser la vision du monde extérieur (local expérimental) à travers le prisme et de mettre à profit les capacités techniques du système pour créer un fond proche de la réalité opérationnelle, contrôlé et identique pour tous les sujets. Pour ce faire, des prises de vues ont été réalisées au magnétoscope lors de vol basse altitude (60 m), très basse altitude (15 m) à une vitesse d'environ 150 km/h avec des survols de bois et de champ, des suivis de lisières. Des évolutions importantes en vol stationnaire ou dynamique ont également été enregistrées.

2.2.2.1. Déroulement des expérimentations

Le sujet est assis dans un siège d'hélicoptère. Après l'application d'électrodes placées de part et d'autre de chaque oeil sur le plan horizontal médian. Pour l'étalonnage, le sujet fixe alternativement son regard sur deux points distants de 40° selon deux modalités servant de référence : en vision binoculaire, (condition naturelle) et en vision monoculaire, l'oeil gauche étant occulté.

2.2.2. EFFETS DES IMAGES DE FOND SUR LA MOBILITE OCULAIRE

Comme il était prévisible, un nystagmus optocinétique a été observé lors de la présentation d'image de défilement devant des lisières de bois. La consigne était de lire ces images comme lors d'un vol réel. Les deux phases classiques du nystagmus étaient présentes.

Phase de suivi du paysage pendant des temps de 1/2 à 2 secondes, dans le sens du défilement. Leur amplitude varie d'environ 3 à 15°.

Phase de retour rapide consistant en un repositionnement de l'oeil dans le sens opposé au défilement du paysage. L'amplitude est de 2 à 10° pour une durée inférieure à 1/10e de seconde.

2.2.3. LA SYNERGIE OCULAIRE

Elle vise à mettre en évidence les rapports entre les déplacements oculaires des deux yeux lorsque seul le droit est soumis à une activité de poursuite continue. Un réticule circulaire généré en balayage cavalier apparaît au centre de l'écran, son diamètre est de 2° et son épaisseur de 6'. Il a une trajectoire horizontale au centre de l'écran, son mouvement, à vitesse constante (8°/s), est alternatif et son amplitude est de 5, 10, 15 et 20° par rapport au centre de l'écran. L'ensemble du cycle dure 30 s et il est répété 3 fois. La consigne est de suivre fidèlement avec l'oeil droit le déplacement de ce réticule. L'oeil gauche est occulté ainsi que la face externe du prisme. Le fond d'image est l'enregistrement de vol à très basse altitude. Le sujet doit appuyer sur une précelle à chaque changement de direction du réticule, ces signaux sont recueillis sur la table traçante.

2.2.3.1. Résultats

L'oeil droit assure une poursuite fidèle du réticule. Au cours des répétitions, du fait de l'apprentissage, un effet d'anticipation sur la poursuite du réticule se manifeste. Le comportement binoculaire est tel qu'il pouvait être prévisible : les deux yeux se déplacent simultanément. Cependant, pour quelques sujets, il a été constaté un ralentissement de l'oeil gauche lors du changement de direction du réticule.

Lors de la poursuite oculaire, les gyromètres captent quelques mouvements du casque, horizontaux et verticaux. Les déplacements horizontaux apparaissent chez l'ensemble des sujets. Leur vitesse ne dépasse guère 10°/s et ce pendant environ 1/2 s. Ces mouvements se déclenchent en général après l'inversion de la trajectoire et l'indication de ce changement par le sujet donc lorsque l'oeil repart en sens inverse.

Dans la majorité des cas, il ne s'agit pas d'un mouvement isolé mais d'une suite de déplacements alternatifs d'amplitude décroissante. Le mouvement initial correspond probablement à une activité réflexe de poursuite ; par contre, il se peut que les suivants soient dus à l'inertie du casque.

D'autre part, pour certains sujets, il a été observé que le fait d'appuyer sur la précelle déclenchait une contraction réflexe de l'ensemble du corps : elle est directement prise en compte par les gyromètres bien que n'appartenant pas précisément à un comportement visuel. Dans ce cas, les mouvements sont essentiellement verticaux, d'une durée de 0,5 à 1 s avec une vitesse inférieure à 5°/s.

Pour les mouvements de tête, il est possible de conclure que :

En dehors de la situation d'activité générale, les mouvements de tête selon l'axe vertical sont peu nombreux et leur vitesse est faible. Les mouvements de tête horizontaux sont plus nets. Toutefois, leur faible amplitude ne permet pas de leur attribuer un rôle dans la prise d'information visuelle.

Il a été demandé aux sujets d'observer de façon prioritaire l'image de fond tout en assurant la détection des changements de direction du réticule. Le sujet est dans ce cas plus libre de la stratégie oculaire puisqu'il lui est demandé de regarder l'image de vol enregistrée comme il le ferait en pilotage. Les sujets montrent une activité oculaire assez faible avec des mouvements de fixation saccadique d'environ 10° d'amplitude.

Les deux yeux ont des comportements tout à fait symétriques. Il existe des mouvements de la tête, principalement horizontaux, plus nombreux, d'une durée en générale assez longue. Ceci les différencie de la situation précédente où ils étaient brefs et plus rares. Les déplacements verticaux sont quasiment inexistants.

La tâche manuelle d'indication de changement de direction effectuée par le sujet est ici moins exacte dans ce contexte expérimental. Les réponses anticipées ou absentes sont plus nombreuses que lors du suivi prioritaire du réticule.

2.2.4. RIVALITE INTER-OCULAIRE

Le sujet est mis dans une situation tendant à provoquer une rivalité binoculaire marquée. La stimulation de l'oeil droit est identique à celle de la première, c'est-à-dire : image monochrome verte (80 cd m-2) avec une tâche de poursuite continue et vision au loin, ne nécessitant pas d'accommodation.

En position basse à 30 cm du sol et à 1 m de l'oeil gauche (à 10° de l'axe) se trouve un compteur dont les chiffres sont lumineux et indiquent un décompte de secondes. L'émission est orange et la luminance est de 21 cd m-2. Ce compteur figure pour le sujet l'emplacement d'un élément d'une planche de bord. Le noir est fait dans la pièce. La tâche effectuée par le sujet est double : il doit suivre le réticule de façon prioritaire.

Il doit signaler l'apparition sur le compteur des nombres de secondes terminés par 0 et 5. La fréquence de consultation est laissée à son initiative. Il ne doit appuyer sur la précelle validant une bonne lecture qu'à la vue du 0 ou du 5.

Les deux images perçues respectivement par chacun des yeux diffèrent donc en terme de luminance, longueur d'onde, forme d'image et support de tâche. Il existe un certain parallélisme entre cette situation et celles rencontrées lors d'un pilotage réel avec partage de source d'informations entre le visuel de casque et une planche de bord.

2.2.4.1. Résultats

La poursuite du réticule :

Elle est effectuée de façon correcte par des mouvements oculaires continus. L'amplitude en est tout de même réduite par rapport à l'expérimentation synergie inter-oculaire (2.2.3.). De même, on constate parfois un retard de quelques degrés entre l'oeil et le réticule. Les changements de direction de la poursuite sont très amortis.

La lecture du compteur :

La stratégie de décompte était laissée à l'initiative du sujet. Certains ont fait jouer leur intuition du temps, d'autres ont organisé celle-ci à l'aide d'un comptage. Le résultat en sera soit une observation toutes les 5 secondes ou bien une succession d'observations avec une fréquence de 1 à 3 par 5 secondes.

La durée de fixation varie selon les sujets de 0,3 à 1 s. Les temps plus longs sont observés chez ceux préférant attendre quelques dixièmes de secondes pour que le 5 ou le 0 apparaisse. Pour l'ensemble des sujets, la régularité des tops de lecture est bonne quelle que soit la stratégie retenue.

Les sujets avaient pour consigne de garder, autant que faire se pouvait, la tête droite telle que la situation opérationnelle pourrait le demander (caméra thermique extérieure à l'aéronef asservie aux mouvements du casque).

De fait, les mouvements de tête horizontaux sont inexistants chez certains sujets, très légers pour d'autres, bien que le compteur nécessite une déviation du regard de 30° vers le bas, et jusqu'à 30° vers la gauche (10° d'écart à l'axe et 20° d'excursion).

LA SYNERGIE OCULAIRE :

Lorsque l'oeil droit est dominant, de par la consigne qui lui impose de suivre le réticule, on observe que, pour un parcours de 40° du réticule, l'oeil droit ne parcourt que 31°, l'oeil gauche seulement 28°. La trajectoire de cet oeil gauche est donc réduit de 10 % par rapport au droit.

Lorsque c'est l'oeil gauche qui est dominant (lecture du compteur) le parcours théorique est toujours de 40°. En fait, l'oeil gauche fixateur décrit 42° et l'oeil droit seulement 32°. La différence de parcours est ici de 25 %. Les écarts observés dans la réduction de course sont à rattacher à la nature du travail effectué : tâche de poursuite dans un cas, lecture fine dans l'autre. Systématiquement, l'amplitude de la trajectoire de l'oeil non sollicité est moindre que celle de l'oeil qui doit prendre l'information prioritaire.

Enfin, les sujets ont, dans une très large proportion, décrit une sensation de neutralisation de l'image non observée au profit de l'autre. Aucun sujet n'a déclaré avoir perçu une superposition ou une fusion des deux images présentées dans les conditions expérimentales décrites. Ces résultats confirment l'impossibilité d'une perception simultanée de deux sources d'informations très différentes vues par chacun des deux yeux. En outre, la lecture altérée met probablement en jeu des mécanismes complexes et inhabituels dont la sollicitation doit se faire de façon prudente.

2.2.5. RIVALITE DE COHERENCE DES INFORMATIONS MONOCULAIRES

Le "Visuel de casque" est un dispositif mis au point pour présenter au pilote une image inhabituelle. En effet, il sera conduit à observer le monde extérieur à travers un dispositif électronique (LLTV ou FLIR) sous un champ réduit avec en surimpression des informations synthétiques (alphanumériques). L'ensemble étant une image virtuelle rejetée à l'infini.

"Comment sont perçues de telles informations par le pilote ?" est la question que l'expérimentation se propose d'aborder. Il s'agit là en effet d'une double tâche monoculaire : perception d'une image du paysage et d'une image synthétique en vision paracentrale.

Pour ce faire, huit lettres sont présentées succéssivement en bordure de l'écran et d'aller selon la disposition ci-contre :

L A F
U   Z
P T I

Le cycle de présentation est constant : L.I.A.U.Z.T.P.F.

Il est demandé au sujet de regarder la région centrale de l'écran et d'aller lire la lettre dès son apparition, de nommer cette lettre, puis de revenir en position centrale.

Le rythme d'apparition est commandé par l'expérimentateur pour trois répétitions du cycle : la première et la dernière se font à une allure lente toutes les 2 à 3 secondes, la deuxième à une allure plus élevée, environ toutes les secondes.

L'apparition de la lettre sur l'écran est marquée sur l'enregistrement graphique pour mesurer le délai de réponse qui s'écoule jusqu'au début du mouvement oculaire.

Il existe une double perspective pour cette expérimentation :

- observation des déplacements oculaires lorsque la stimulation est unique dans des conditions d'activité oculaire de <u>recherche ponctuelle</u> différant donc de l'expérimentation précédente qui concernait une observation continue,
- les lettres des bords verticaux apparaissent selon un angle de ± 20°. Il est intéressant d'observer si la lecture de ces lettres provoque un mouvement réflexe de la tête visant à rapprocher axe visuel et axe frontal de la tête. Ce réflexe est constaté habituellement dès que la cible est à plus de 15° de l'axe visuel.

2.2.5.1. <u>Résultats</u>

Lors du premier cycle de lettres, le délai moyen du début de la saccade est, selon les sujets, de 0,3 à 0,5 s, encore que les délais de 2 à 3 s ne soient pas rares. La durée de fixation pour la lecture est d'environ 0,5 s.

Pour les cycles suivants, qui sont des répétitions avec les mêmes lettres dans un ordre identique, on observe [illegible]rtain apprentissage marqué par l'anticipation des positionnements oculaires, des délais de réaction [illegible]fs. L[illegible] période de fixation se stabilise vers 0,3 s. On observe également de fausses anticipati[illegible]palement lorsque la succession est effectuée à rythme assez lent, en moyenne toutes les 3 s.

Pour l'ensemble des sujets, les deux yeux ont des comportements symétriques durant les trois répétitions en ce qui concerne l'amplitude, la vitesse et la forme des déplacements oculaires. Les sujets n'ont pas évoqué de gêne particulière à la lecture des suites de lettres.

Les mouvements de tête ne se manifestent que pour les déplacements rapides de l'oeil Les déplacements verticaux de la tête se font dans ce cas à une vitesse d'environ 10°/s sur une durée moyenne de 0,5 s. Les horizontaux sont effectués à une vitesse moindre 5°/s mais sur de plus longues durées, 1,5 s.

Le caractère réflexe de cette activité est montré par la réduction quasi générale des mouvements de tête avec la réalisation des répétitions effectuées par le sujet.

2.3. <u>ENTRETIENS AVEC LES SUJETS</u>

A l'issue de chaque expérimentation, les impressions des sujets étaient recueillies à l'aide d'un questionnaire semi-ouvert. Seuls les élements les plus saillants sont rapportés.

2.3.1. <u>EXPERIENCES SUR LES TYPES DE RIVALITES</u>

Pour les expériences suivantes moins éloignées des circonstances de vol, les opinions ont été plus nombreuses.

Systématiquement, le réticule a été perçu sur un plan plus proche du sujet que celui de l'image enregistrée. Aucune cause optique ne pouvant produire d'ecart objectif. L'origine de ce phénomène est de nature psychophysiologique. Deux voies sont à explorer : la qualité de l'image et sa nature cognitive.

Des contrastes existent entre les composantes de l'image présentée ici : contraste de luminance, contraste de définition, contraste cognitif.

Le contraste de luminance : pour que la symbologie soit bien différenciable du paysage filmé, sa luminance était plus élevée. Or, les différences de luminance sont un facteur commun dans l'appréciation de la position relative des objets.

La définition de l'image fond enregistrée est bien inférieure à celle du réticule. Il se crée un "contraste de définition", dont l'influence sur la perception a déjà été illustrée lors d'études sur la détection de cible et l'analyse d'image selon leur niveau de structuration.

Il n'existait aucune relation formelle ou conceptuelle entre symbole et image de fond. Ceci est illustré par la difficulté ressentie par les sujets à observer simultanément les deux.

Le suivi du mouvement du réticule et le défilement du paysage n'ont pas paru intégralement réalisables simultanément. Lorsque la priorité est donnée au suivi du réticule, le sujet perçoit les

changements de surface du paysage mais ne peut préciser les détails apparus sur l'image. Si l'observation du paysage l'emporte, la détection des mouvements du réticule est moins précise.

Une observation alternative pourrait être réalisée selon l'avis de certains sujets. Ceci appellerait d'autres situations expérimentales car il s'agissait ici, il faut le rappeler, d'un réticule sans rapport symbolique ou dynamique avec l'image de fond.

Le suivi du réticule s'est parfois trouvé à l'origine d'une illusion. Lorsque le trajet du réticule et le mouvement du paysage étaient opposés ou concourants, le sujet ne savait pas à coup sûr distinguer le mouvement relatif résultant. Il s'en suivait une réponse éronnée ou absente.

2.3.2. LA CONSULTATION ALTERNATIVE

La consultation alternative du compteur et de l'image enregistrée a montré l'établissement généralisé d'une neutralisation de l'image non lue puisque aucun des sujets n'a perçu les deux images fusionnées ou même superposées.

Certains sujets ont évoqué une remanence oculaire de l'image du réticule lors de la lecture du compteur. Il s'agit là d'un phénomène physiologique sans rapport direct avec la vision binoculaire telle quelle est envisagée ici.

Il a également été observé par quelques sujets que l'aisance du passage de la lecture du compteur à celle du réticule est plus grande que pour l'opération inverse.

3. EXPERIMENTATIONS EN VOL

L'évaluation en laboratoire a montré une dégradation de l'activité perceptive d'un sujet équipé d'un visuel de casque. Mais le vol réel fait intervenir une masse de facteurs beaucoup plus importante. Il est donc nécessaire d'étudier le comportement d'un pilote aux commandes d'un hélicoptère avec, comme seule source d'information visuelle, l'image du capteur vidéo associé.

Toutefois, le vol en hélicoptère impose une instrumentation de mesure légère et rend difficile toute répétition stricte des mesures expérimentales. Aussi, l'accent a-t-il été mis sur des situations simples à créer où pouvaient être évalué :

- l'effet des dégradations de l'acuité visuelle et du sens de la profondeur lors de différents types de vols,

- la comparaison entre les différentes configurations de vision possibles avec le visuel de casque,

- une observation permanente des interactions visuel de casque - pilotage permettant de constater des phénomènes spécifiques à cette situation.

3.1. FONCTIONS ETUDIEES

Trois fonctions importantes pour le pilotage à basse altitude ont été retenues comme critères représentatifs. Il s'agit de l'évaluation par le pilote de l'altitude, de la distance le séparant d'obstacles et de la vitesse de son déplacement.

3.1.1. L'EVALUATION DE L'ALTITUDE DE VOL

Plusieurs paramètres ont été jugés pertinents et ont fait l'objet de variations expérimentales au cours de deux types de vol :

en translation :

- selon deux vitesses : 60 ou 90 nds,
- en plein champ ou en suivi de lisière,
- selon des altitudes de 3 à 30 m, soit environ 10 à 100 pieds.

en vol stationnaire : devant une haie ou sur une aire aménagée marquée H.

Ces mesures sont effectuées dans deux contextes :

- pilote équipé actif : le pilote porteur du visuel de casque doit placer la machine à une altitude de consigne, puis tenir celle-ci en vol stabilisé. La lecture de la radio-sonde permet de comparer altitude de consigne et réponse du sujet,

- pilote équipé passif : le pilote non équipé stabilise la machine à une altitude consigne que le pilote équipé doit évaluer le plus rapidement possible. Dans ce cas également, il y a comparaison entre altitude de consigne et réponse du sujet.

Le port de l'équipement interdisant la lecture de la planche de bord, et plus particulièrement de la radio-sonde, le pilote ne peut se baser que sur ses propres sensations. D'autre part, aucune indication n'étant donnée au pilote sur la qualité de sa réponse, il lui est impossible de corriger son jugement. La succession d'altitudes proposées ou demandées est aléatoire.

Le déroulement des vols sur des repères de paysage tels que champs ou lisières permet aux pilotes de conserver l'usage de leurs indices habituels. Ils sont en effet entraînés au vol à très basse altitude où la taille et la texture des champs ainsi que des lisières sont des éléments informatifs.

3.1.2. EVALUATION DE LA DISTANCE

Cette mesure est effectuée en vol de translation sur différents objets : pylones, lisières, véhicules, habitations. Il est inopinément demandé au pilote d'évaluer très rapidement la distance le séparant de tel obstacle. Toutefois, aucun dispositif de mesure de distance n'étant monté sur l'hélicoptère d'essai, il est impossible de confronter objectivement évaluation et réalité. Le pilote de sécurité constitue la référence de comparaison ; la pratique d'essais de tir, d'évitement d'obstacles lui fournissant une grande expérience de l'estimation visuelle de distance.

3.1.3. EVALUATION DE LA VITESSE DE DEPLACEMENT

Son appréciation repose elle aussi sur la qualité optique de la chaîne image vidéo et sur l'analyse d'indices perceptifs extraits du champ visuel réduit. Il est demandé au sujet d'estimer la vitesse de translation lors de vols stabilisés. L'indicateur de la vitesse - air est la référence objective. Son emplacement le rend invisible au pilote-sujet. Aucune indication n'est fournie sur la qualité de la réponse.

3.2. DEROULEMENT DES ESSAIS EN VOL

3.2.1. LES SUJETS

Les sujets sont quatre pilotes d'essais, âgés de 34 à 44 ans et ayant de 2000 à 5500 heures de vol. Ils ont participé aux expérimentations en laboratoire.

Afin de les familiariser à la pratique du vol avec l'équipement étudié, chacun d'eux a effectué quatre vols d'entraînement. Cette phase d'apprentissage était laissée au rythme propre de chacun des pilotes. La perspective était de les amener à voler en sécurité de façon aussi proche que possible du vol tactique. Il est à noter qu'aucune des tâches qui leur sont demandées lors des expérimentations proprement dites n'a été évoquée durant cet entraînement de façon à ne pas provoquer de facilitation particulière.

3.2.2 LE MATERIEL EXPERIMENTAL

L'hélicoptère retenu pour les essais en vol est une ALOUETTE III. Un pilote de sécurité est présent lors de tous les essais pour reprendre les commandes en cas de défaillance humaine ou technique. Il veille au déroulement correct du vol et assure la surveillance de l'environnement de la machine. Il assure le pilotage lorsque le sujet est en situation passive et place la machine aux altitudes définies par l'expérimentateur présent à bord. Enfin, il constitue la référence pour certaines évaluations.

3.3. RESULTATS

L'expérimentation a comporté deux vols d'environ une heure pour trois des quatre pilotes, et un vol seul pour le quatrième. Les conditions météorologiques et techniques, les délais experimentaux n'ont pas permis d'effectuer pour chaque pilote les mêmes successions des différents types de vols ni de recueillir pour chacun d'entre eux le même nombre de données.

Aussi n'a-t-il pas été possible de traiter statistiquement les observations ; des tendances seules sont indiquées, elles sont présentées sous forme de nuage de points permettant de comparer les consignes avec les réponses des sujets.

3.3.1. ALTITUDES EN PIEDS

Les estimations sont présentées tous sujets confondus dans trois contextes :

- à 60 noeuds en survol de champs,
- à 60 noeuds en suivi de lisières,
- à 90 noeuds en survol de champs.

La comparaison stricte entre la réponse fournie par le sujet et l'indication de la radio-sonde en vue d'indiquer un taux d'erreurs n'est pas possible ; le sujet estime un ordre de grandeur de l'altitude en valeur arrondie : ainsi une réponse de 40 pieds peut être donnée pour des hauteurs réelles comprises par exemple entre 36 et 43 pieds. Cette "fourchette" évolue selon les pilotes et pour les individus selon l'altitude. La lecture du cadran de radio-sonde peut être faite à plus ou moins 2 pieds. Toute quantification précise de l'erreur serait de fait erronée. Ces résultats sont donc à considérer comme des tendances.

3.3.1.1. Vols en suivi de lisière à 60 noeuds (figure 2)

On constate de façon marquée que les sujets actifs placent leur appareil à une altitude supérieure à celle de la consigne indiquée. Ils surestiment. A l'inverse, pour les sujets passifs, la valeur d'altitude qu'ils donnent est inférieure à la réalité. Ils sous-estiment.

3.3.1.2. Survol de champs à 60 noeuds (figure 3)

La même distinction est observée entre les réponses des sujets actifs et celles des sujets passifs. Toutefois, la dispersion des réponses est différente pour les deux cas. Les sujets actifs surestiment leur réponse d'une façon assez dispersée avec des écarts pouvant atteindre le triple de la valeur réelle. Les sujets passifs sous-estiment de façon prédominante ; l'écart maximum est indépendant de l'altitude de consigne.

3.3.1.3. Survol de champs à 90 noeuds (figure 4)

Les conditions sont sensiblement les mêmes que pour une vitesse de 60 noeuds. Surestimation et sous-estimation marquées avec écarts plus importants pour la première tendance et résultats plus précis pour la seconde. L'augmentation de 50 % de la vitesse ne semble pas altérer ou améliorer notablement l'estimation de l'altitude pour les sujets.

3.3.1.4. Vol stationnaire sur aire d'atterrissage (figure 5)

Les réponses sont assez justes jusqu'à 40 pieds du sol, au-delà, la surestimation du pilote actif est plus variable. Le nombre restreint d'observation avec pilote passif ne permet de dégager de tendance précise au-dessus de cette altitude.

3.3.1.5. Vol stationnaire devant une lisière (figure 6)

La lisière utilisée est la même pour tous les essais. La cîme des arbres est en moyenne à 30 pieds. L'entraînement au vol à très basse altitude des pilotes-sujets de cette expérimentation les conduit à une appréciation assez précise de leur altitude par rapport à une lisière dont ils connaissent la hauteur des composants : branches maîtresses, cîmes selon le type d'arbre. De fait, la justesse des appréciations est meilleure que dans les situations précédentes et la dichotomie sujet actif/passif s'estompe. L'importance du système de référence connu est ici déterminante. Ces appréciations justes en vol stationnaire s'opposent à celles obtenues en vol de translation avec pourtant le même objet de référence de hauteur, la lisière.

3.3.2. DISTANCES EN METRES (figure 7)

La valeur de référence est la quantification effectuée par le pilote non équipé entraîné à ce genre d'évaluation. La réponse est celle fournie par le pilote équipé du visuel de casque en situation active.

On observe une précision élevée dans l'estimation des distances inférieures à 100 m pour des objets connus. Les quelques mesures d'objets lointains donnent lieu à une surestimation pouvant aller jusqu'à 100 %.

Ces résultats concernant l'appréciation des distances sont à comparer à des études antérieures sur le sujet. En situation passive, GIBSON et BERGMAN (04) avaient montré que des élèves pilotes sous-estimaient toujours les distances, et ce, même en vision binoculaire. En situation active, GROSSLIGHT et Coll. ont observé une surestimation en monoculaire et une sous-estimation en binoculaire lors d'un poser de roue sur cible.

Par rapport à cette dernière étude, nos pilotes en monoculaire estiment correctement les courtes distances (inférieures à 100 mètres) et ne surestiment, comme les sujets de GROSSLIGHT, qu'à grande distance. Si on considère l'étude de GIBSON avec des élèves, on peut noter que nos pilotes sont en situation partielle d'apprentissage. Ils sont actifs et donnent des résultats différents. Au total du rapprochement de ces trois types d'études effectués dans des contextes très différents mais avec la même finalité, on ne peut que tirer la conclusion qu'il s'agit de phénomènes très complexes. Il semble bien que ce soit un phénomène d'intégration corticale.

Enfin, compte tenu que ces expérimentations ont été faites de jour en ambiance nettement photopique, il paraît difficile de les rattacher aux observations faites sur la mauvaise appréciation des distances en vol de nuit.

3.3.3. VITESSE DE DEPLACEMENT (figure 8)

Le pilote est périodiquement invité à évaluer la vitesse. Ces observations ont été pratiquées entre 20 et 100 pieds, sans systématisation.

Les estimations sont correctes dans l'ensemble. Il semblerait toutefois qu'une surestimation se produise avec l'élévation de la vitesse.

3.3.4. TEST D'ACUITE VISUELLE

Il nous a paru intéressant de vérifier le pouvoir séparateur de l'oeil équipé en ambiance réelle. A l'issue de chaque vol, un test d'acuité visuelle angulaire sur anneaux de LANDOLT a été pratiqué.

L'hélicoptère était posé et le rotor en mouvement. L'acuité dans ces conditions est en moyenne de 2/10e MONNOYER. Cette valeur est légèrement supérieure à celle observée en laboratoire. La luminance supérieure du test en plein air explique sans doute l'amélioration constatée.

3.4. OBSERVATIONS SUR LES VOLS D'ESSAIS

Il a été possible de recueillir auprès des pilotes qui volaient pouur la première fois avec un tel dispositif des informations quant à l'apprentissage de son utilisation. En outre, ces pilotes ont évoqué les contraintes sur le domaine du vol et des évolutions.

Enfin, dans une configuration particulière de vision à l'aide du visuel, une illusion a été constatée.

3.4.1. APPRENTISSAGE

Les quatre vols préalables effectués par tous les pilotes sujets constituent pour chacun d'entre eux la prise de contact en vol avec le visuel de casque qui se caractérise par une restriction du champ visuel (30° x 40°) et une restriction non négligeable du pouvoir séparateur de l'oeil (2/10e).

Les pilotes ont connu une habituation très rapide de pilotage avec le visuel. L'apprentissage le plus important avait lieu au cours du premier vol.

Le niveau de performances atteint après quatre vols était tout à fait satisfaisant puisqu'il a autorisé des vols à très basse altitude (15 mètres). L'apprentissage s'est également manifesté par la possibilité d'effectuer des vols de durées accrues à mesure des répétitions avec une réduction de la fatigue ressentie. Les pilotes décrivent leur progression en terme d'économie de mouvements de tête, de facilité de manoeuvre dans des domaines plus proches du vol naturel binoculaire.

Cette phase n'a pu donner lieu à une étude systématique dans le but d'observer et de quantifier les progrès et les stratégies selon les pilotes. Ceci reste à faire. Il faut sur ce point se garder de généraliser. Les sujets sont tous pilotes d'essais et de ce fait, habitués à s'adapter rapidement à un dispositif de vol particulier. Une population moins spécialisée pourrait rencontrer d'autres problèmes.

3.4.2. CONTRAINTES SUR LE VOL

Un court entretien avec chacun des pilotes en fin d'expérimentation permet d'évoquer les types de manoeuvres rendues plus difficiles, voire impossibles avec le visuel de casque :

- les atterrissages et décollages rapides, le contour d'obstacles, le vol à très basse altitude (inférieur à 30 pieds), les virages à droite et gauche accentués sont déclarés plus difficiles,

- les virages à très forte inclinaison supérieure à 45°, l'arrêt rapide sur obstacle et le poser sur un point précis non marqué semblent pratiquement impossibles.

A noter ici que l'arrêt rapide et le poser sans référence supposent une nette appréciation des distances et des grandeurs et nous avons vu à quel point l'image fournie handicapait cette perception.

3.4.3. OBSERVATIONS D'UNE ILLUSION

A la fin de chaque vol, le pilote était mis en situation binoculaire avec la chaîne image du visuel en fonctionnement et un filtre atténuateur sur l'oeil gauche. Le filtre était choisi de façon à atténuer l'écart de luminance entre les deux yeux.

Le pilote disposait donc d'une vision binoculaire à champ réduit (30° x 40° pour chaque oeil) caractérisée par la vision d'une image artificielle sur l'oeil droit et naturelle sur l'oeil gauche.
Dès la mise en place de cet aménagement, les pilotes exprimaient un sentiment de confort très marqué (ceci intervenant après 45 mn de vol monoculaire). Un vol à basse altitude sur un champ de blé était effectué bien volontiers. Mais l'estimation de l'altitude par le pilote était erronée : se croyant à 5 mètres, celui-ci volait allégrement à 1 ou 2 mètres des épis de blé et ce à une vitesse variant de 80 à 90 noeuds.

Lors d'un posé sur l'aire balisée connue, un pilote s'est estimé à 3 m lorsque les roues ont touché. Cette évaluation fausse a été si prégnante que le pilote a écarté l'information donnée par les vibrations dues à l'effet du sol en l'attribuant à un changement d'axe du vent.

Ce glissement d'information est tout à fait propre à une illusion sensorielle. Cette configuration binoculaire a donc induit une forte surestimation de la profondeur chez les quatre pilotes dans des conditions comparables. Cette perception allait bien au-delà de la surestimation qui, pour de si faibles altitudes, n'avait jamais provoqué d'aussi grands écarts entre perception et réalité.

3.4.3.1. Hypothèses sur l'illusion observée

Pour expliquer cette illusion, on peut évoquer le stéréophénomène de PULFRICH décrit en 1923, les contrastes et les fréquences spatiales évoqués par BLACK et CORNACK (02), la disparité des tailles des images rétiniennes (FOLEY et Coll.(03)).

Les pilotes observaient le monde à travers deux images dont la différence de niveau lumineux était dans un rapport d'environ 20 (oeil droit équipé/oeil gauche avec filtre neutre). C'est bien là, la base du stéréophénomène de PULFRICH.

Les contrastes des images sont différents pour l'oeil droit et pour l'oeil gauche en effet, la gamme de contraste disponible sur la télévision est plus réduite que celle observée pour l'oeil gauche (vision directe du monde extérieur). Par ailleurs, les fréquences spatiales perçues par les deux yeux sont différentes : l'oeil droit est handicapé par rapport à l'oeil gauche.

Enfin, si l'on considère que l'échelle 1/1 à travers le dispositif optique n'était obtenue que pour des distances supérieures à 10 m, en-deçà, on peut trouver des situations de disparité de taille d'image entre les deux yeux. Les altitudes de vol lors de l'observation de l'illusion étaient inférieures à 10 m.

3.4.3.2. Synthèse sur les hypothèses

En conclusion, chacune des sources de disparité citées peut être à l'origine d'une illusion de profondeur dans un contexte particulier. Or, toutes ces disparités se retrouvent avec le "visuel de casque" utilisé en vision binoculaire. Certaines différences sont à noter : les expérimentations utilisent des mobiles se déplaçant sur un axe perpendiculaire au regard, alors que l'hélicoptère crée un mouvement de l'image parallèle au regard, donc une image allant de haut en bas, composée de lignes plutôt horizontales, les expérimentations privilégiant les lignes verticales. Les hypothèses présentées par les différents auteurs mettent en avant des paramètres, sens du déplacement, orientation, contrastes dont les modalités effectives sont mal connues. Dans un tel contexte, il n'est donc pas possible d'attribuer l'illusion observée à un facteur de façon préférentielle. Il s'agit davantage d'une intrication de l'ensemble.

CONCLUSION

L'évaluation a porté sur une maquette représentative dans son architecture générale des dispositifs prévus pour permettre le vol tactique en hélicoptère de nuit.

Le fait majeur à retenir est que les pilotes ont pu effectuer des vols avec ce dispositif. Mais il existait des limitations aux évolutions. Le coût, en charge de travail supplémentaire, n'a pas été évalué directement. Mais les observations cliniques et la description des phénomènes élémentaires permettent de déduire qu'il est loin d'être négligeable. La réduction de cette charge de travail est difficile car les mécanismes qui l'induisent sont mal connus.

Certaines dégradations des performances sont liées à l'état de la technique du matériel utilisé. On peut s'en affranchir en menant des expérimentations selon d'autres protocoles. Ainsi l'effet de la réduction du champ a été étudié en vol sans utiliser ce matériel (PAPIN et Coll. (10)).

D'autres contraintes sont inhérentes à la conception même du dispositif. Ainsi la difficulté pour se situer dans l'espace, des solutions palliatives doivent donc être d'ores et déjà recherchées.

L'idée maîtresse est de fournir au pilote des compléments d'informations pour suppléer celles qui ne sont plus disponibles. C'est ce à quoi tendent les études désignées sous le nom générique de symbologie (PAPIN (09), SANTUCCI (11)).

Ainsi, de part sa démarche conjointe de laboratoire et de terrain, cette étude permit de recenser les problèmes majeurs qui donneront lieu à des développements technologiques et des études centrées sur les facteurs humains.

REMERCIEMENTS

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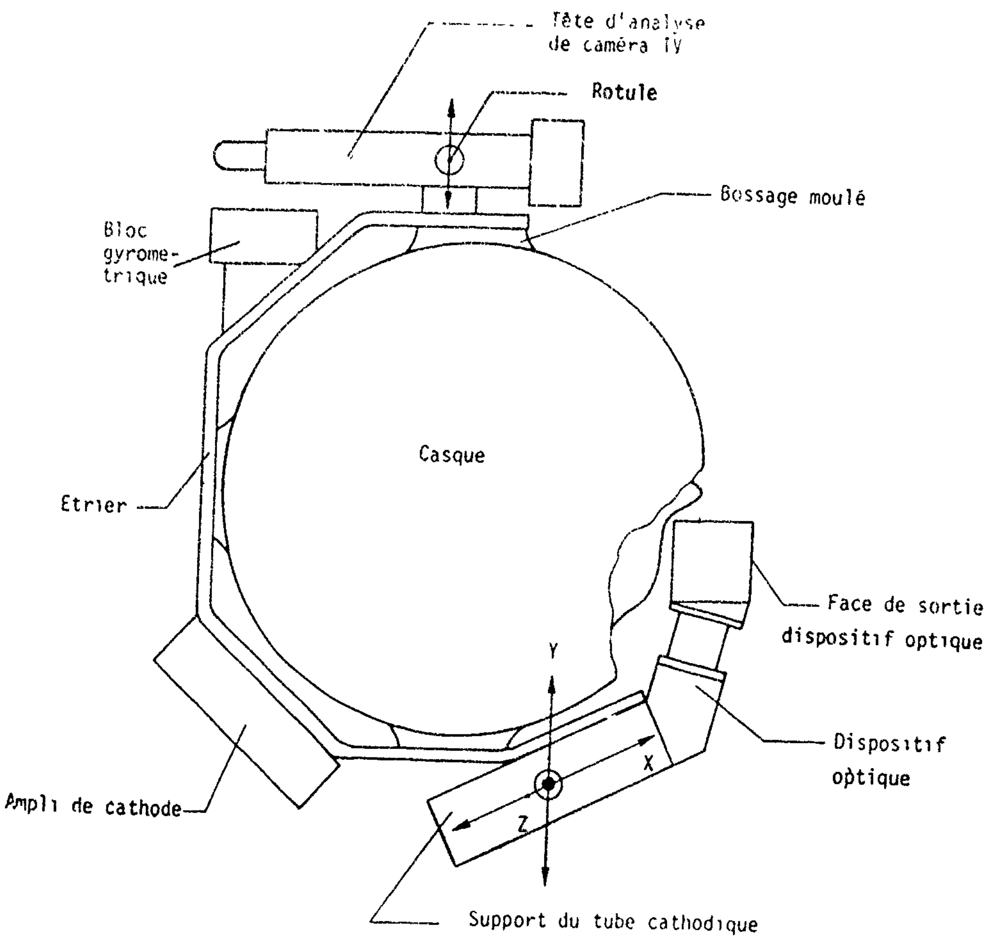


FIGURE 1 : SCHEMA DU "VISUEL DE CASQUE"

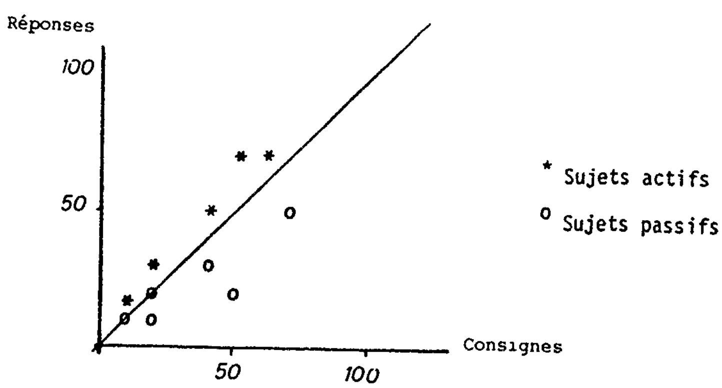


FIGURE 2 : ESTIMATION DE L'ALTITUDE EN PIEDS
LORS DE VOL A 60 NOEUDS EN SUIVI DE LISIERE

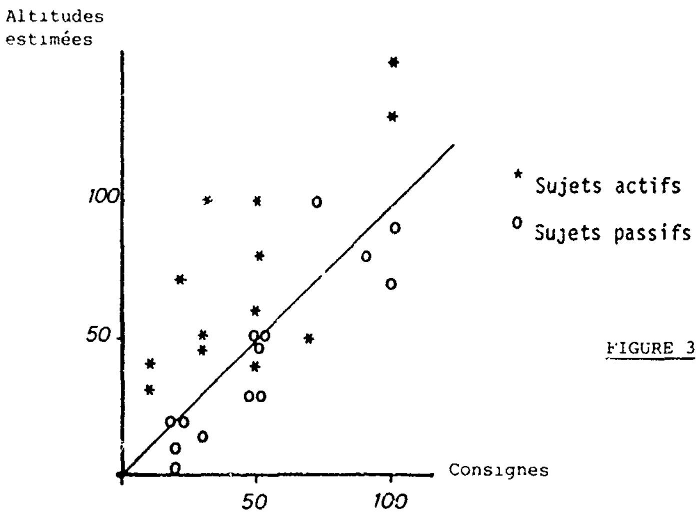
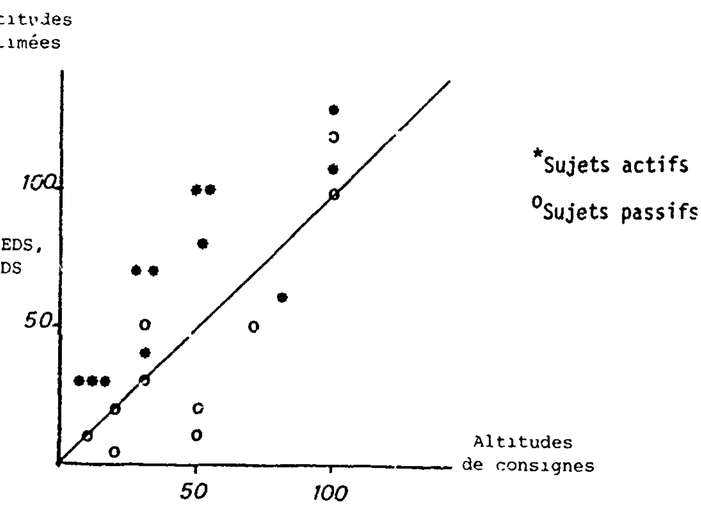


FIGURE 3 : ESTIMATION DE L'ALTITUDE EN PIEDS EN SURVOL DE CHAMP A 60 NOEUDS

FIGURE 4 : ESTIMATION D'ALTITUDE, EN PIEDS, EN SURVOL DE CHAMP A 90 NOEUDS



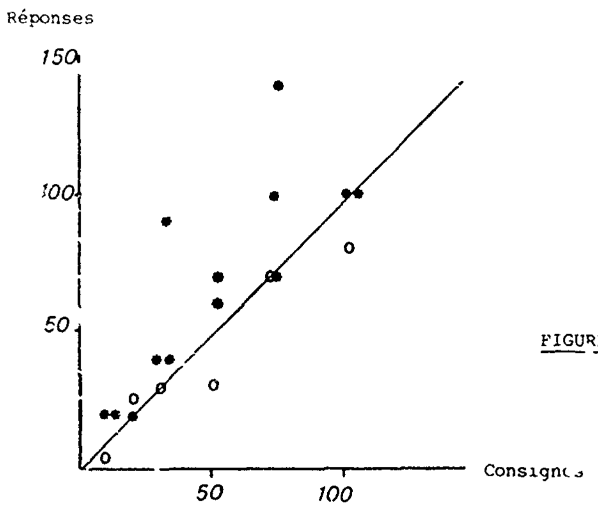


FIGURE 5 : ESTIMATION DE L'ALTITUDE EN VOL STATIONNAIRE SUR AIRE D'ATTERRISSAGE

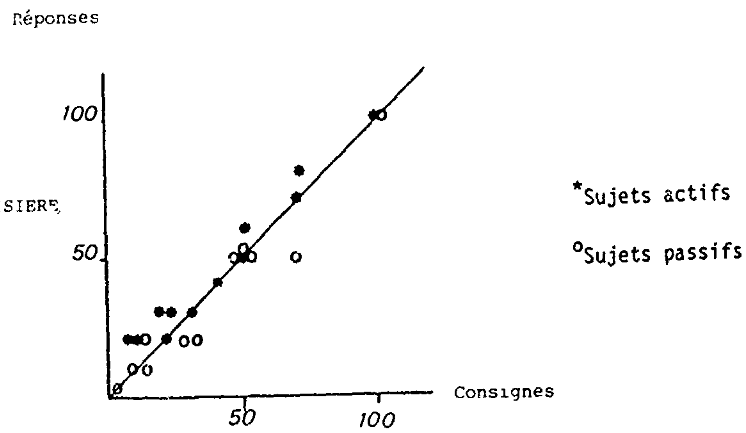


FIGURE 6 : ESTIMATION DE L'ALTITUDE EN VOL STATIONNAIRE DEVANT LISIERE

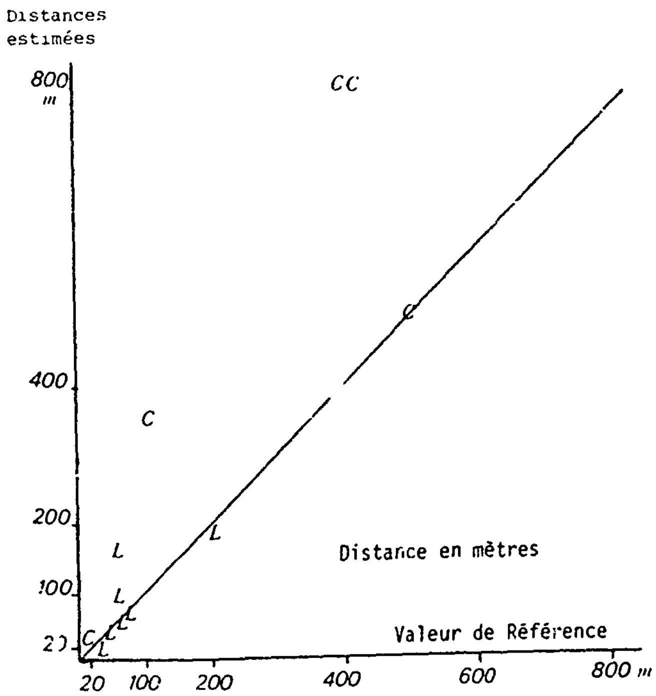


FIGURE 7 : ESTIMATION DE DISTANCES EN METRES

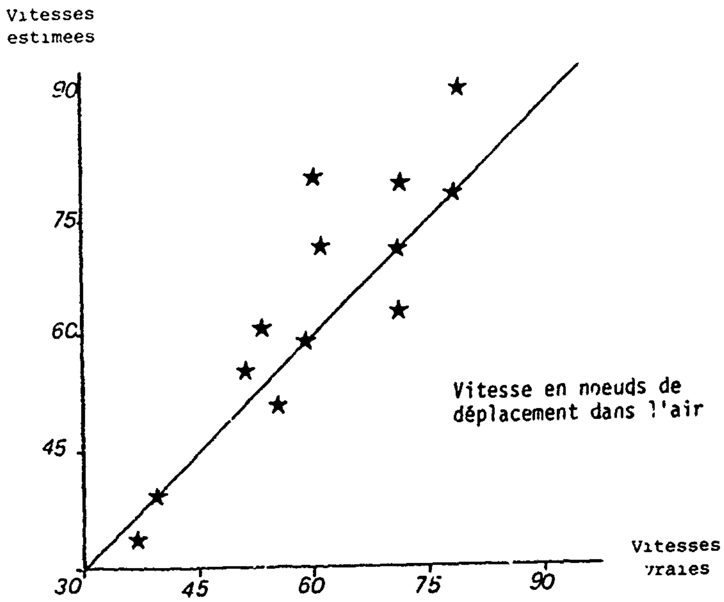


FIGURE 8 : ESTIMATION DE VITESSES

DISCUSSION
Papers 1—4

1. Major Verona - USA - Image Intensifiers: Past & Present.
2. Dr Bohm - Germany - FLIR, NVG and HMS/D Systems for Helicopter Operation.
3. Capt Haidn - Germany - Operational Experiences with Night Goggles in Helicopter Low-Level Flight at Night.
4. Dr Santucci - France - Evaluation d'une Maquette de Visuel et Casque pour Helicoptere.

Brennan UK: You say that you do not like blue-green lighting and are adopting a fluorescent system lit by UV. Do you not encounter problems with autokinesis?

Haidn GE: Yes, I know this problem but we always fly with visual contact whilst using sensors, so we have reference to the outside scene and we did not see any illusions when looking at the UV lit instruments.

Bohm GE: What was the UV light? Can you see this light from the outside? An enemy could see UV light if he had special detectors.

Haidn GE: We could see the UV light inside the cockpit but it would not be detected as easily as the blue-green light. At about 250m we can see the blue-green lit cockpit, but not the UV lit cockpit. So we prefer, for the time being, UV lighting, but things may change.

Psimenos GR: Did you have any accidents directly connected with NVG's, and my second question, do you use sleeping pills for day relaxation of pilots operating at night?

Haidn GE: Let us answer the second question first. We do not prescribe anything for the pilots rest, we only give them time to do what they want. They start in the late afternoon, fly their mission and go back home and in addition to this we give them a second free day during the week. They do not have duty on the Friday and have a long weekend, that is all we can do at the moment. To answer the first question, yes we did have one accident and we believe that the cause of this accident was a navigational problem.

Brincker DE: If the pilot is looking at an explosion flash, will he be blinded?

Haidn GE: No. With the second or third generation goggles there is no blinding effect. We only have blinding effects whilst looking directly into a bright source. If you move your head so that this source is out of the field of view there will not be any blinding effects.

Bohm GE: What was the field of view of the helmet mounted display which you used?

Santucci FR: 40 degrees horizontal and 40 degrees vertical, a square.

Bohm GE: Did you find this view good for flight trials.

Santucci FR: Yes, oddly speaking and it came as a surprise to us, obviously the workload was much increased but flight was feasible in the experimental flights. We have conducted a trial with a similar kind of device under the same operational flight conditions, flight was also feasible but of course there was a change in the visual techniques for retrieving information. It was necessary to consult the instrument panel many more times in order to extract information on speed and altitude. The second part of the study has confirmed what I have presented in my talk, that the development of the experiment is justified.

Brennan UK: With your low light television and FLIR did you present the image to one eye, to both eyes, and if you only presented it to one eye did you occlude the other? Did you have any problems in other words with retinal rivalry or with the competing imagery degrading that of the FLIR?

Bohm GE: In answer to the first question, yes it was a monocular display of 30 x 40 degrees with a good image. It was a prototype of a Ferranti display, but at that time it did not have a beam splitter like the Honeywell helmet mounted sight. We did not find rivalry with the other eye at night. The left eye cannot see because it is dark; in twilight, rivalry can exist, but we have not encountered it. If the alignment of the helmet sensors to the line of sight of the pilot and to the platform sensor is not correct then you may also have rivalry, but we have not found this.

Brennan UK: Of course you were working in very dark luminances so you would not, but under twilight conditions did you get conditions whereby peoples' attention was shifting from one eye to another? When they were able to appreciate the imagery was the image degraded by looking at the twilight scene with the other eye?

Bohm GE: We only made 3 to 5 flight trials at twilight, especially in the morning and at night. During daytime the cockpit was completely dark for the co-pilot, but the pilot had a view of the outside world. To your comment, I did not think that 90 degrees was good for a helmet mounted display as the eye can appreciate colour over 90 degrees, which I have mentioned in my paper. I think 30 x 40 degrees is a restricted field of view as normally you see 180 degrees with both eyes, but at the edge you only see movement. If you have obstacles in the scene then you can get problems, if you see them only at the edge of the picture. I think Capt Haidn can add something to this.

Haidn GE: Yes, if I may I will add something. I do not agree with what you said Dr Bohm because if the display gives an image of 40 degrees the human eye is not able to detect this 40 degrees all the time. I

think that there will be only a small part sharply visible, about 10 degrees. We have to move our eyes on the HMD to get the whole information from the display and that creates a problem with the symbology. If the symbology is at the corner you have to move the eye far to the right or left side, so we have to think very carefully about the symbology on such displays.

Bohm GE: I have something to add. I think you can see sharply in a limited field of only about 1 to 2 degrees, but the eye is scanning the information. If the electro optical sensor is static and not moving with the platform you can only see the whole field of 40 degrees and I think that it is not enough. I think it is better to have 60 degrees. If you have an obstacle at the edge of this image you can see it much more quickly, especially if you are flying NAP of the earth, but if you move your head very often then of course it is not necessary.

Haidn GE: May I state a second time that I think we have to consider the role in which this device is used. If we are forced to go into a terrain with obstacles, we have to have a wide field of view if there is no sensor movement. I personally believe we cannot fly this mission without a swivel mount on the sensor, because in the vicinity of obstacles you have to move the picture to clear the obstacles whilst flying, so I think it is useless to discuss fixed sensors in conjunction with low level flight.

Santucci FR: I want to make a comment regarding the field of view. It was 40 degrees, we would have liked 60 degrees because the helicopter pilot with peripheral vision would pick up a lot more information. We made an experiment and some men were consulting other panel instruments to get more information which they were lacking, particularly information regarding speed and altitude. So they require more information. Obviously you must explore the whole outside world over 180 degrees, therefore the sensor should be a mobile and swivelling one. It would be quite wrong to set the display on the instrument panel because whenever you looked to the right side the camera would look to the right whereas the whole proprioceptive system is telling you that the image is in front, there is mis-matching and therefore you would have sensory illusions.

Verona US: From the technical side we must remember that as we increase our field of view with the same sensor and the same display we decrease our resolution, so it was one of the trade-offs we originally had with the NVGs where the display had originally a 60 degrees field of view. However the users demanded better resolution, more detail, so we had to shrink the field of view to 40 degrees, this was the trade-off that they accepted. We had the same problem with our FLIR, we can give you a 60 degree field of view but we have the same number of resolution elements in 60 degrees as we had over 40 degrees, the pilots require more resolution.

Bohm GE: Why does the LH6 programme have a requirement of 60 x 110 degrees? If you are right about the technical and physical limits the resolution of the sphere will reduce if you use a bigger field of view, or if you go to a smaller detector which is also possible.

Verona US: What you want and what you get may not be the same. What you want and what you can afford may not be the same.

Bull UK: I have a question for Dr Santucci concerning your experiment with depth perception and your three bars. Can you tell me at what distance was the target and did you take steps to avoid any perception of depth by other means, for instance, the length of the centre bar appearing to change as it moved forwards and backwards.

Santucci FR: The perception distance was about 10m. Obviously with this Howard Dolman type device we see to it that the height and the size of the bar should not be perceived by the operator, only the relative position. We were very careful with the lighting of the bar so that it should be perceived on a uniform basis whatever the position of the bar. We have been using such a method contrary to the stereoscopic visual acuity method which would have been completely wrong in such a case. We employed such a method because we thought it was more representative of the integration of a number of factors which come into the actual perception of depth. I would like to make an additional comment concerning the definition of the images. I would like to draw your attention to the fact that our subjects were operating with a visual acuity of 2/10th, so the famous one minute angle considered necessary for the accurate interpretation of displays was not achieved. Of course they were not informed of their results. They actually had excellent vision, which was highly degraded and I believe that the image should be steadied and improved. It seems to me that more objective experiments should be undertaken to clarify this problem. Interviewing pilots alone would not be sufficient. We should do more experiments in order to check, to verify in an objective way, what they are telling us in their reports.

Haidn GE: I have a question for Major Verona. What is the transmittance of the filter integrated in the ANVIS optic?

Verona US: The cut off filter is currently set for 600nm. There is a curve, it is a cut-off curve so it is not 0% and then 100%. It transmits from about 590nm to 610nm and you achieve about 95% transmission beyond 610nm and less than 1% below that.

VISUAL AND SPECTRORADIOMETRIC PERFORMANCE CRITERIA FOR NIGHT VISION GOGGLES (NVG) COMPATIBLE AIRCRAFT INTERIOR LIGHTING

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SUMMARY

The U.S. Naval Air Development Center has developed a draft military specification for NVG-compatible aircraft interior lighting under U.S. tri-service sponsorship. The specification is based on the utilization of a specific type of NVG, namely the AN/AVS-6 Aviator's Night Vision Imaging System (ANVIS). This paper describes the performance requirements and testing methodology established in the specification and the rationale for developing these requirements.

The performance requirements are affected by three factors: luminance, chromaticity, and ANVIS compatibility. Luminance requirements do not change drastically from the requirements that presently exist for interior lighting. However, the chromaticity requirements of green for primary and secondary lighting, and yellow for both master caution and warning indicators are different from those that presently exist. The reason for this change is that any lighting with a significant amount of red energy cannot be used in a cockpit that is required to be ANVIS-compatible. The implications for this new color design for cockpit lighting are discussed together with the rationale for the chromaticity coordinates and limits chosen.

ANVIS compatibility is defined in terms of the spectral sensitivity of the ANVIS and the combination of spectral radiance of the cockpit lighting and outside world night radiance. Quantitative testing methodology for determining ANVIS compatibility of cockpit lighting is also discussed. A thorough description of all analytic and laboratory studies performed in support of this specification development will be presented in this paper.

PREFACE

The military establishment is constantly striving to improve the operational capability of its forces. The ultimate goal is to provide fighting forces with the capability to conduct operations around the clock and under adverse weather conditions. For the last 12 years aircrews have been utilizing NVG as a piloting aid to allow them to fly aircraft during clear nighttime conditions.

In 1973, the U.S. Army adopted the AN/PVS-5A NVG (see figure 1) as an interim pilot's aid. Although these NVG provided the necessary imagery to allow the pilots to fly low-level night flights, there were several inherent problems. The most critical of these problems was the incompatibility of the cockpit lighting and the inability to look outside (to view terrain) and inside the cockpit (to view the instrument panel) without refocusing the NVG.

Realizing that the NVG significantly increased the capability of helicopter pilots to perform their missions at night, the U.S. Army decided to develop a pair of NVG specifically for helicopter pilots. These NVG are known as the AN/AVS-6 ANVIS (see figure 2).

The ANVIS has alleviated many of the problems associated with the AN/PVS-5A, with the exception of incompatibility with present aircraft lighting. When utilizing the ANVIS, the pilot looks through the image intensifier to view the terrain outside the aircraft. To view the interior of the cockpit the pilot simply looks around or under the image intensifier tubes with the unaided eye as shown in figure 3. Therefore, in order to allow aircrews to utilize the ANVIS, the spectral radiance of the cockpit lights must be such that the lights do not interfere with the image intensification characteristics of the ANVIS, yet provide proper lighting to enable the pilot to adequately acquire information with the unaided eye when viewing the interior of the cockpit.

BACKGROUND

The ANVIS is a passive, helmet-mounted, binocular image intensification device that utilizes third generation image intensification tubes. The ANVIS is extremely sensitive to ambient radiance in the 600 to 900 nanometer (nm) wavelength portion of the electromagnetic spectrum (orange to near infrared). The ANVIS has a 40° circular field-of-view (FOV) with a nominal resolution of 36 line pairs per millimeter. Basically, the ANVIS operates by converting the photons of the outside night scene into electrons with a S-20 photocathode, amplifying the electrons with a microchannel plate, and converting the electrons back into visible light with a P-20 phosphor screen. A diagram of this process is shown in figure 4. Because the ANVIS intensifies light sources up to 30,000 times, bright lights can produce a severe veiling glare that will obscure the image [1]. In order to prevent this, and to protect the image intensifier tubes, the ANVIS is provided with an automatic gain control (AGC). The AGC decreases the sensitivity of the image tubes when they are exposed to bright lights that emit energy in the

ANVIS-sensitive portion of the electromagnetic spectrum. Therefore, whenever the ANVIS is exposed to cockpit lighting that is too intense between 600 and 900 nanometers in wavelength, the AGC is activated, the ANVIS becomes less sensitive to the radiance of the outside scene, and the pilot is no longer able to see outside the cockpit. In order to achieve compatibility of the cockpit lighting with the ANVIS, the cockpit lighting should have a spectral radiance with little or no overlap into the spectral response of the ANVIS image intensifier tubes. However, in order to allow the cockpit to be viewed with the unaided eye, the light should be optimal for the luminous efficiency of the photopic eye. Figure 5 graphically presents these considerations.

Because of the spectral response characteristics of the ANVIS, red, orange and white cockpit lighting is highly amplified. The brightness and spectral characteristics of existing aircraft lighting causes the AGC of the ANVIS to activate, thus ANVIS cannot be used with cockpit lighting as it is presently configured. In order to alleviate this problem and provide compatibility with the method of ANVIS operation, the cockpit lighting has to be modified or redesigned to reduce cockpit lighting spectral output in the ANVIS-sensitive portion of the electromagnetic spectrum.

Many different methods have been attempted to achieve ANVIS-compatible aircraft lighting. For instrument lighting, the successful methods include floodlighting and bezel lighting using filtered incandescent lights and electroluminescent (EL) panels. For edge-lit panels, filtered incandescent lighting, EL lighting and light emitting diodes (LEDS) have been successfully used. Some manufacturers have even developed daylight readable/ANVIS-compatible displays and indicators. ANVIS-compatible lighting components are available from many different manufacturers and these devices have been successfully used to fly with ANVIS in a variety of different types of aircraft, including helicopters and fixed-wing aircraft [2,3]. However, as of this date there is no agreed-upon lighting standard to which aircraft manufacturers or purchasers can refer to define ANVIS-compatible aircraft lighting. Many procurement documents simply tell the manufacturer to make the aircraft lighting "NVG-compatible." The manufacturer is left to his own devices to determine first, what "NVG-compatible" means, and second, how to design this type of lighting. This has led to a variety of different types of methods that have been used to manufacture and verify ANVIS-compatible lighting components, some of which are better than others.

Because a standard method of defining and measuring ANVIS compatibility was needed, funding was provided in April 1983 to begin work on a lighting standard. This work has led to the development of a draft tri-service U.S. military lighting specification [4] that defines performance requirements for compatibility in terms of the spectral sensitivity of the ANVIS and the spectral radiance of the cockpit lighting. The specification define- 'antitative testing methodology for determining ANVIS compatibility.

DISCUSSION

When defining ANVIS-compatible aircraft interior lighting there are a number of interactions that must be considered. When a pilot utilizes the ANVIS in an aircraft, energy from both the outside world and the cockpit lighting enters the ANVIS. In addition to viewing this image, the eyes also receive energy from the cockpit lighting. The development of an ANVIS-compatible cockpit lighting system requires careful balancing of the energy the eye receives from the ANVIS and the aircraft lighting. The draft lighting specification addresses these issues by specifying the amount of spectral radiance that the lighting system is permitted to emit in the ANVIS-sensitive portion of the electromagnetic spectrum, and for unaided eye viewing, the color (chromaticity) and luminance of the lighting system.

Spectral Radiance Limitations

For the purposes of defining spectral radiance limitations, the specification defines a new quantity: ANVIS radiance, defined in units of AR. ANVIS radiance represents the amount of energy emitted by a light source that is visible through the ANVIS. It is defined as the integral of the curve generated by multiplying the spectral radiance of a light source by the relative spectral response of the ANVIS:

$$\text{ANVIS radiance} = \int_{450}^{930} G_r N \, d\lambda \quad (\text{AR}) \tag{1}$$

where:

G_r = relative ANVIS spectral response
N = spectral radiance of light source ($W/cm^2 \cdot sr \cdot nm$)
$d\lambda$ = wavelength increment (nm)

To calculate the ANVIS radiance, the relative spectral response of the ANVIS must be defined. The spectral response of the ANVIS is governed by two factors: the spectral response of the image intensifier tubes, and the spectral transmission of the objective lens. The spectral response of the image tubes was determined by using data provided by the U.S. Army Night Vision and Electro-Optics Laboratory. An average response curve for each of the two tube manufacturers, plus the response curve for an extremely sensitive ("hot") image tube were provided. These three curves were normalized and plotted on the same graph. At each 5-nm increment, the largest value of the three curves was determined. These values were used to generate a composite, normalized image tube response curve. Production image intensifier tubes can be expected to have a normalized spectral sensitivity somewhat lower than this curve.

During the manufacturing process, a "minus-blue" filter (i.e., a filter that blocks blue-green light and transmits red light) is built into the ANVIS objective lens.

This filter has been designed and incorporated into the production ANVIS to reduce the amount of blue-green cockpit light that enters the ANVIS. The transmission of this filter is defined in the ANVIS procurement specification. The filter transmission curve representing the maximum amount of transmission allowed by the specification was multiplied by the image tube sensitivity curve to yield a total ANVIS sensitivity curve, shown in figure 6. These data are used in equation (1) for calculating ANVIS radiance.

The specification defines compatibility in terms of ANVIS radiance. As a baseline, it was decided that compatibility could be achieved if the image of the cockpit lighting, when viewed through the ANVIS, were no brighter than the outside scene. Therefore, the ANVIS radiance produced when viewing an outside scene had to be defined. Operational experience has shown that, because of its low reflectivity, a defoliated tree is the terrain feature that is the most difficult to see at night. The ANVIS radiance of a starlit defoliated tree was calculated by multiplying the spectral radiance of starlight [5] by the reflectivity of tree bark [5] and inserting this value for N in formula (1). The calculation yields an ANVIS radiance of 1.7×10^{-10} AR. Therefore, if it is desired that the cockpit lights should be no brighter than the outside scene when viewed through the ANVIS, the ANVIS radiance of the cockpit lights should not exceed 1.7×10^{-10} AR when illuminated to produce an acceptable level of luminance for unaided eye viewing. U.S. Air Force tests have shown that the level of luminance required for cockpit lighting systems, when pilots are using ANVIS, is less than 0.1 foot lambert (fL) (0.34 candela per square meter (cd/m^2)). Therefore, the specification requires compatibility when devices are luminated to produce 0.1 fL (0.34 cd/m^2).

In special cases, cockpit lighting components are required to be visible when viewed through the ANVIS. Components in this category include warning lights, master caution lights and head-up display (HUD) systems. Visibility of warning and master caution lights is required to be certain that the pilot does not overlook the onset of a warning or caution event. The HUD is required to be visible through the ANVIS so that the pilot can see information on the HUD when looking outside the cockpit. The ANVIS radiance requirement for these lighting components was determined based on laboratory experimentation and currently available components. Table 1 is a summary of the ANVIS radiance requirements for various lighting components.

The measurement technique used to check for ANVIS compatibility involves the use of a highly sensitive spectroradiometer. The requirements for the spectroradiometer [4] include traceability to the National Bureau of Standards (NBS). This requirement assures that measurements will be repeatable from manufacturer to manufacturer. In general terms, the test procedures require that the lighting component be energized to produce a given luminance, and the spectral radiance is measured using the spectroradiometer. The ANVIS radiance is calculated using formula (1), and if the value falls within the requirements shown in Table 1, the device is compatible with the ANVIS.

The specification also outlines procedures to be used during the cockpit lighting mockup evaluation as a final check for ANVIS compatibility. During the lighting mockup, a procedure is used to verify that the cockpit lighting does not degrade the resolution characteristics of the ANVIS.

Table 1 - ANVIS Radiance Requirements for Aircraft Lighting Systems

Lighting System	Luminance Level for Compatibility (fL)	ANVIS Radiance (AR)
Primary and Secondary Instrument and Console Lighting; Compartment Lighting; Controls; Indicators; Caution and Advisory Signals; Utility Lighting; and Panel Mounted Displays (PMDs) that display flight information only	0.1	less than 1.7×10^{-10}
PMDs that display video imagery	0.5	less than 1.7×10^{-10}
HUD	5.0	between 1.7×10^{-9} and 5.1×10^{-9}
Warning and Master Caution Indicators	15.0	between 1.5×10^{-8} and 4.5×10^{-8}

CHROMATICITY REQUIREMENTS

Chromaticity is a psychophysical term describing the qualities of color associated with hue and saturation. The chromaticity is specified by using the CIE (Commission Internationale de l'Eclairage) diagram which describes a color by the proportions of red (x), green (y), and blue (z) light that are present in the color. Since x + y + z = 1, the values of x and y alone can define the location of a color on the CIE diagram [7]. Because the ANVIS is highly sensitive to colors with radiance at wavelengths longer than 600 nm, any color that excludes radiance with wavelengths longer than 600 nm could be used for compatible lighting. These colors include the blues, greens, and yellows and exclude the reds, non-spectral purples, and white.

However, one goal for specifying the chromaticity of general crewstation lighting should be to produce as uniform an appearance as possible among all cockpit light sources. The primary reason for this is to avoid any unintentional distractions owing to differences in chromaticity. Therefore, one relatively homogeneous section of the CIE diagram should be selected to produce this desired uniformity in chromaticity. As demonstrated by the size of the MacAdam ellipses [8] in this area. the greens appear more uniform than the other colors.

Most studies indicate that luminance is a more important factor than chromaticity in its effect on visual acuity [9]. However, the human eye has been found to be maximally sensitive to light with a dominant wavelength in the middle of the visual spectrum (around 555 nm or yellowish-green for photopic vision). Therefore, to maximize luminous efficiency, consideration should be given to this dominant wavelength over other hues. Another consideration is to endeavor to match the chromaticity of the cockpit lighting with that of the ANVIS viewing screen phosphor (P20), for which x = 0.426 and y = 0.546. An attempt should also be made to closely match the chromaticity of the P43 phosphor (x = 0.336 and y = 0.554), a common phosphor used in monochromatic cathode ray tube (CRT) displays. Again, the reason for these matches is to prevent unintentional distractions. These considerations would place the optimum dominant wavelength for general crewstation lighting in the yellowish-green or yellow-green areas of the CIE diagram as mapped out on the Kelly Chart of Color Designations for Lights [10]. See figure 7.

Another consideration is to try to produce lighting that is as unsaturated as possible (chromaticity coordinates away from the spectrum locus and closer to the equal energy point). Some studies have suggested that reading with highly saturated lighting for long periods of time is irritating and causes eye fatigue [11]. However, to increase contrast for daylight visibility, the use of highly saturated colors for certain cockpit switches and indicators may be necessary.

Another area of the CIE chromaticity diagram needs to be defined for use as master caution and warning signals. These signals must have sufficient radiance to be seen through, as well as around, the ANVIS FOV. Also, it is necessary to provide these signals with a contrast in hue and saturation to the other cockpit light sources. Since the red area would provide too much radiance, it would appear that a highly saturated yellow would be appropriate for this purpose.

After the above factors were considered, the following approximate hue objectives were selected for ANVIS-compatible aircraft lighting:

1. General Interior Lighting
   ANVIS GREEN A - dominant wavelength around 525 nm.

2. Monochromatic Lighting (for sunlight readability and emphasis)
   ANVIS GREEN B - dominant wavelength around 552 nm.

3. Warning and Master Caution Signals
   ANVIS YELLOW - dominant wavelength around 578 nm.

In addition to specifying the hues, it is also necessary to describe the allowable variations in both hue and saturation. Several different options have been proposed. These options range from a small square box to the whole green section of the CIE diagram. If the area is too small, it would be unnecessarily restrictive and would arbitrarily exclude many currently available ANVIS-compatible lighting components. On the other hand, if it is too large, the goal of producing uniform lighting chromaticity would not be achieved. Since it is not possible to meet both of these requirements simultaneously, a reasonable compromise is needed. Accordingly, limits are being described with MacAdam ellipses, since these ellipses approximately represent the ability to visually discriminate color differences. An important factor in determining the size of these ellipses is to consider the chromaticity coordinates of the currently available aircraft lighting devices which are ANVIS-compatible. A compilation of these state-of-the-art components indicates that devices with chromaticity coordinates within the recommended ellipses (including filtered incandescent, electroluminescent, and light-emitting diodes) are achievable. The three lighting chromaticity areas are shown on figure 8. Of course any lighting devices that meet these chromaticity criteria must also meet the spectral radiance limits defined previously, since the chromaticity does not indicate the non-visible spectral composition of the lighting. Table 2 presents a listing of components and the results of laboratory measurements on these components.

TABLE 2 - RESULTS OF LABORATORY MEASUREMENTS OF SAMPLE LIGHTING COMPONENTS

SAMPLE NUMBER	COMPONENT DESCRIPTION	ANVIS RADIANCE ($x10^{-10}$)		CHROMATICITY COORDINATES x	y	
1	Advisory Switch (1)	.652	(P)	.2352	.6571	(P)
2	Advisory Switch (2)	1.038	(P)	.2079	.6548	(P)
3	Caution Switch (1) - top	1.231	(P)	.2790	.6435	(P)
4	Caution Switch (1) - bottom	1.696	(P)	.2921	.6440	(P)
5	Caution Switch (2) - top	72.480	(F)	.3121	.5504	(F)
6	Caution Switch (2) - bottom	3.062	(F)	.3039	.6361	(P)
7	Master Caution Switch - bottom	2765.000	(F)	.4942	.5039	(P)
8	Advisory Switch	1.240	(P)	.2994	.6486	(P)
9	4-94 Filter	48.810	(F)	.3968	.5078	(F)
10	4-96 Filter	1.503	(P)	.2696	.5241	(P)
11	BG-7B Filter	4.387	(F)	.2154	.4618	(P)
12	NV-2 Filter	.560	(P)	.1316	.4491	(F)
13	NV-2A Filter	1.986	(F)	.2351	.5403	(P)
14	NV-2B Filter	1.482	(P)	.1854	.5114	(P)
15	Aviation red lamp, 4-94 filter at 15.0 Fl.	57049.000	(F)	.5581	.3741	(F)
16	EL Strip	13.160	(F)	.2030	.5092	(P)
17	EL Strip w/filter	.415	(P)	.1357	.6284	(F)
18	EL Strip	16.050	(F)	.2114	.5266	(P)
19	EL Panel	.787	(P)	.2357	.6913	(P)
20	EL Ring Light	10.850	(F)	.2123	.4894	(P)
21	P43 (CRT Phosphor) unfiltered	31.851	(F)	.3355	.5538	(F)
22	Filtered incandescent	1.248	(P)	.2655	.5939	(P)

P = passed criterion
F = failed criterion

COLORS DISPLAYS

As stated previously, in order to be ANVIS-compatible, light sources within the cockpit must have no significant amount of radiance between 600 and 900 nm. A multicolor CRT requires the use of three different phosphors - blue, green, and red. Figure 9 shows the spectral radiance curve of the three phosphors combined and a separate curve of the red phosphor. The red phosphor has a range of energy emission from about 580 to 715 nm and a peak at 630 nm. Since this energy would not pass the spectral radiance criterion, a number of possible solutions need to be investigated including: the use of filters, location of the color CRT out of the ANVIS FOV, and switching the red off during periods when the ANVIS is being used, and coding the display information with shapes or shading.

LUMINANCE REQUIREMENTS

The luminance requirements will not change from present standards and specifications except that the caution and advisory signal panels will dim with the instrument lights. The requirements for daylight readability will also not change.

CONCLUSION

In January 1985, the third draft of the military specification [6] was submitted for the formal ratification and approval process of the U.S. Department of Defense. All comments from the U.S. Army, Navy, and Air Force are being reviewed and resolved by the Joint Logistics Commanders' (JLC) ad hoc Group for Aviation Lighting. Industry comments are being collected and coordinated by the Society of Automotive Engineers, Committee A-20A NVG subcommittee, prior to resolution by the JLC. Many of these comments have already been addressed by updating and correcting previous drafts of the specification. Printing and distribution of the final specification should begin before the end of this calendar year, with utilization expected to start in mid 1986.

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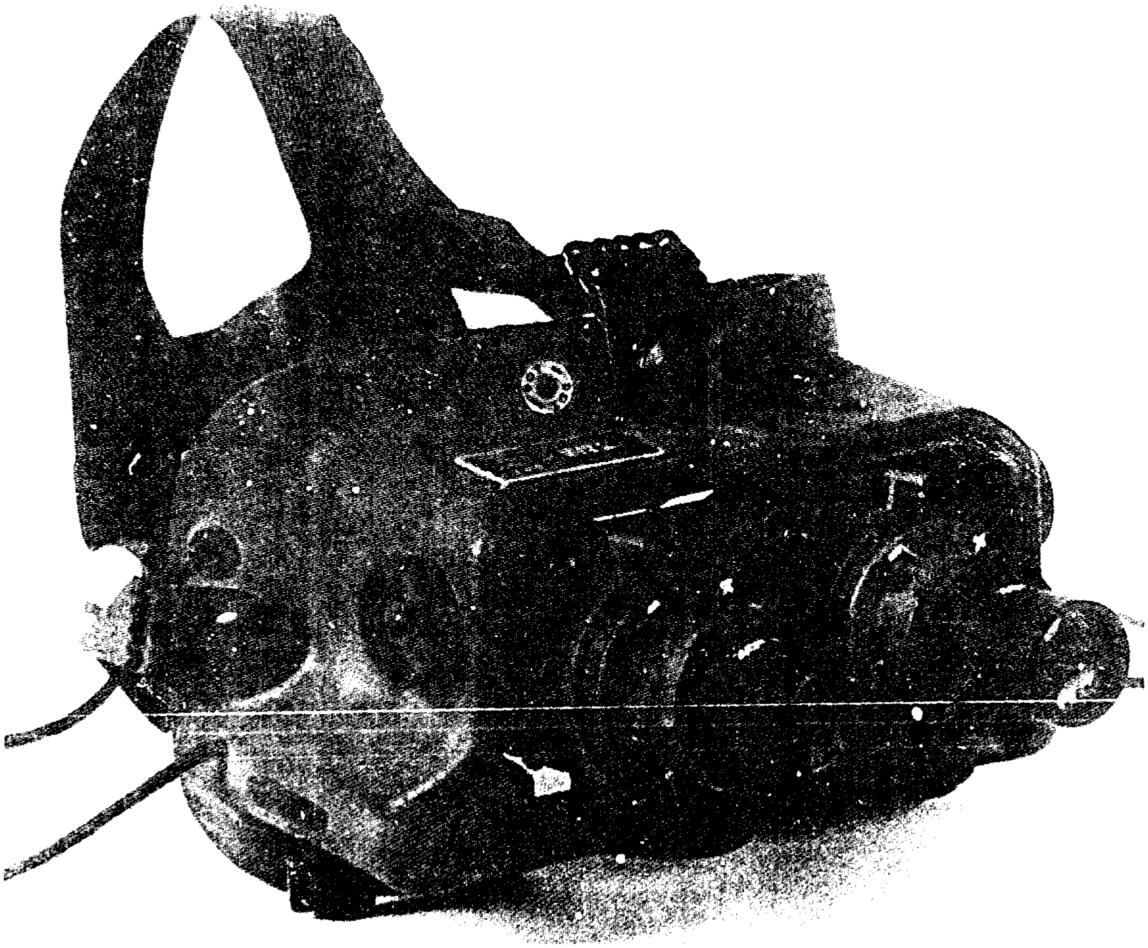

Figure 1 - AN/PVS-5A Night Vision Goggles

Figure 2 AN/AVS-6 Aviator's Night Vision Imaging System

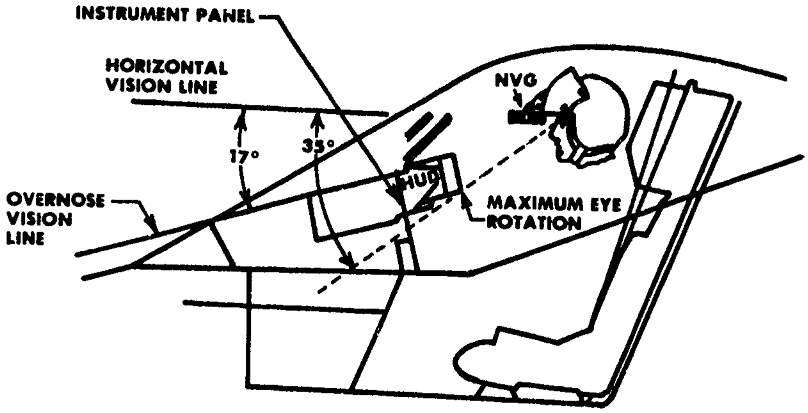

Figure 3 - Look-Around Concept When Using ANVIS

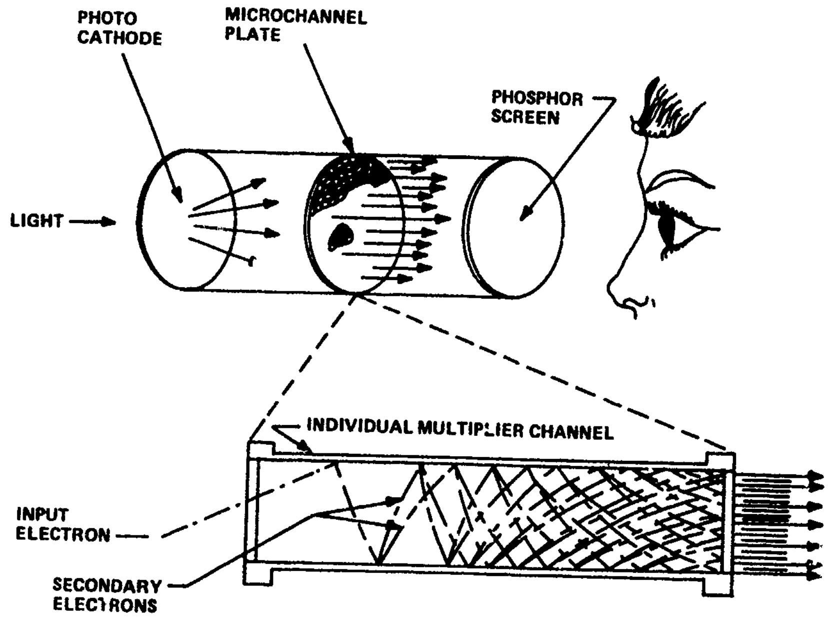

Figure 4 - ANVIS Light Amplification Process

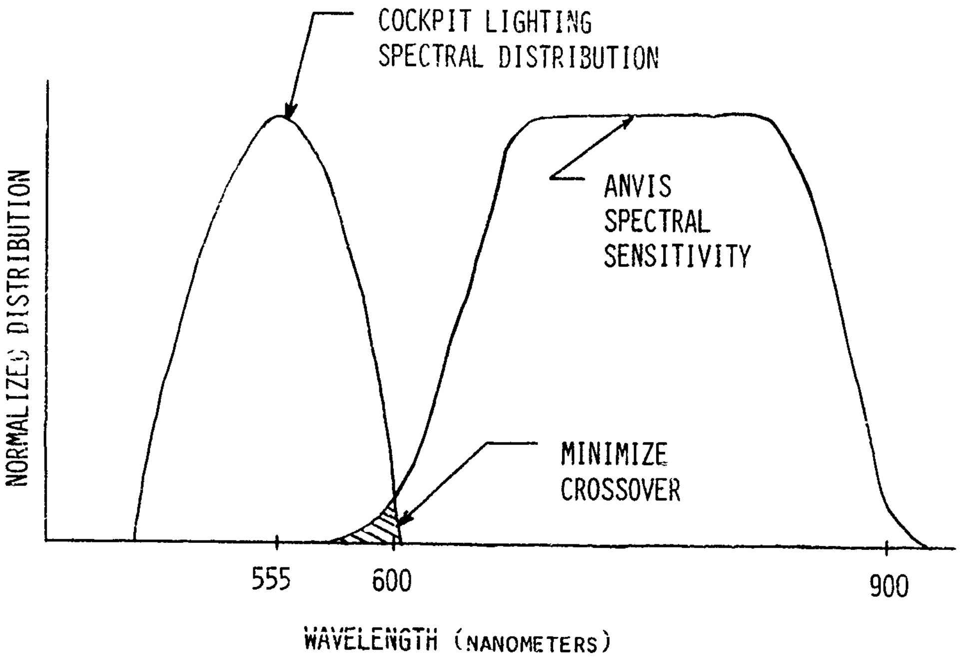

Figure 5 - Conceptual Diagram of the Spectral Distribution of ANVIS-Compatible Cockpit Lighting

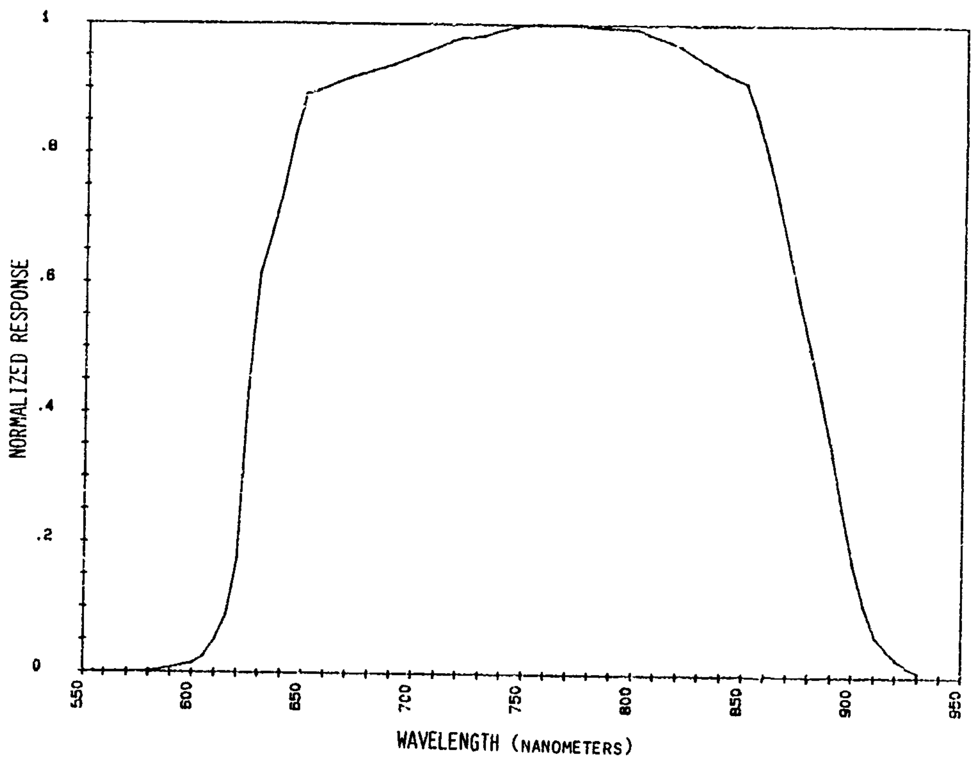

Figure 6 - ANVIS Sensitivity Curve

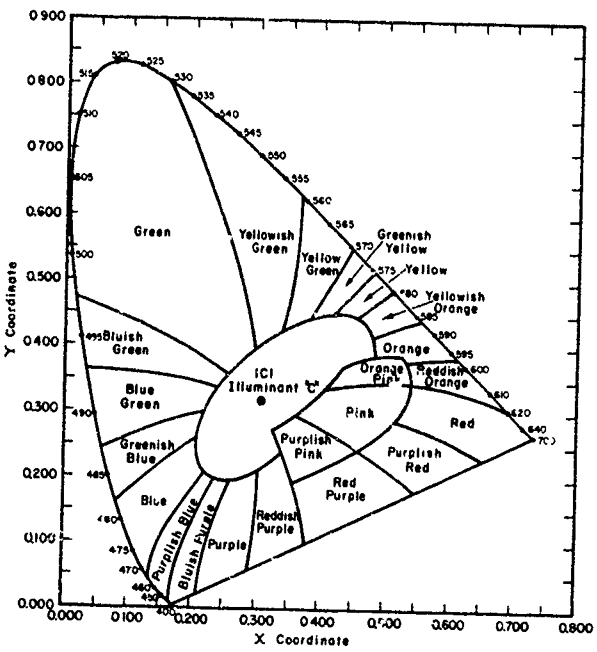

Figure 7 - Kelly Chart of Color Designation for Lights

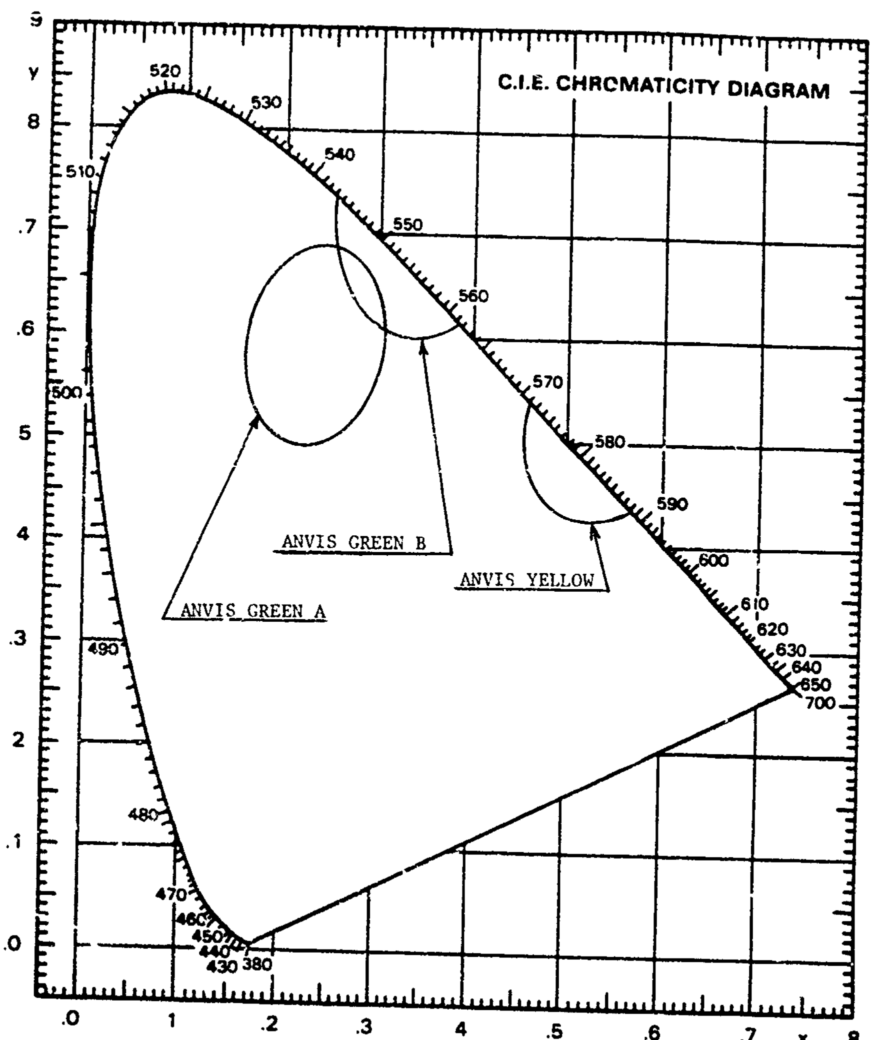

Figure 8 - Ellipses Showing Chromaticity Limits for ANVIS-Compatible Lighting

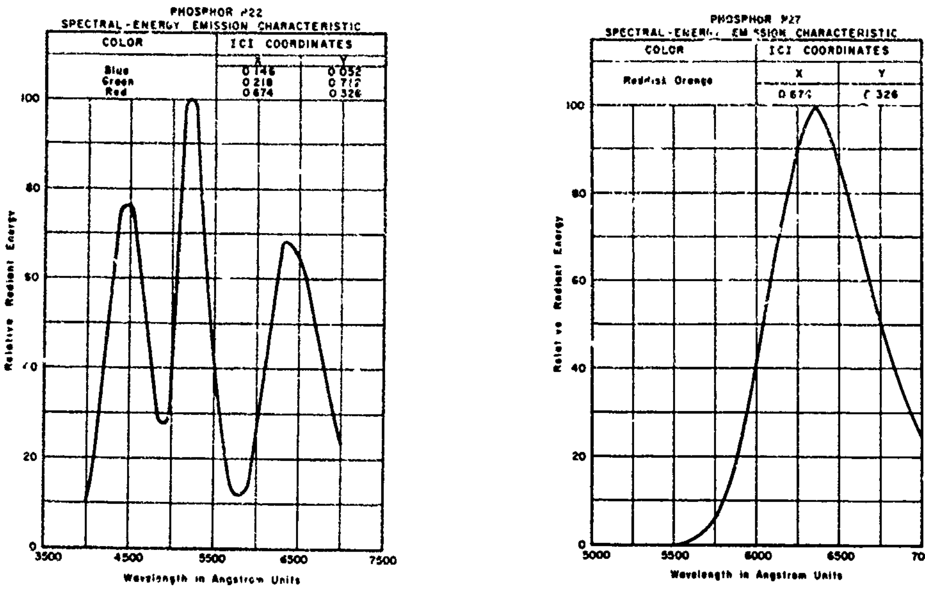

Figure 9 - Spectral Radiance Curves for Phosphors Used in a Color CRT

NIGHT VISION SUPPORT DEVICES HUMAN ENGINEERING INTEGRATION

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SUMMARY

Although Night Vision Goggles (NVGs) extend the luminance range over which we can use our vision, current AN/PVS systems require special cockpit lighting to be fully effective, reduce visual depth of field and diminish the field of view. All three of these factors are extremely important to pilots performing night operations. This paper describes the results of several operationally oriented efforts conducted by the United States Air Force Aerospace Medical Research Laboratory's Human Engineering Division to improve visual performance, cockpit lighting, and flight information transfer in conjunction with the use of night vision goggles. The efforts include an operational definition of NVG compatible lighting, a recommended approach to improving depth of focus, an attempt to expand field of view, and a description of a NVG HUD using optically injected flight data. All efforts center around using or modifying current AN/PVS NVGs used by US forces.

VISUAL PERFORMANCE THROUGH NVGS

Night vision enhancement devices appear to be gaining wide acceptance among both civil and military organizations as means to improve visual perception under conditions of low luminance. The new devices are not merely light amplifiers (light being defined as that portion of the electromagnetic spectrum to which our eyes are sensitive), but extend our capability to see into the near infrared. Because of this differential sensitivity of our eyes and night vision devices, both lighting engineers and night vision device users must be aware of the possible degradations in performance in either the unaided or enhanced visual systems caused by inappropriate lighting schemes. In many cases, inappropriate lighting may cause visual performance through night vision devices to be less than that experienced without the devices in place.

Although the human eye is sensitive to electromagnetic radiation from about 380 nm to about 700 nm, it is not equally sensitive to all wavelengths of light. During daylight or photopic vision, our retinas are maximally sensitive to light whose wavelength is about 555 nm (a yellow-green). During night, or scotopic vision, our retinas are maximally sensitive to light whose wavelength approaches 505 nm (a blue-green). Figure 1 shows the relative spectral and energy sensitivities of the photopic and scotopic visual systems.

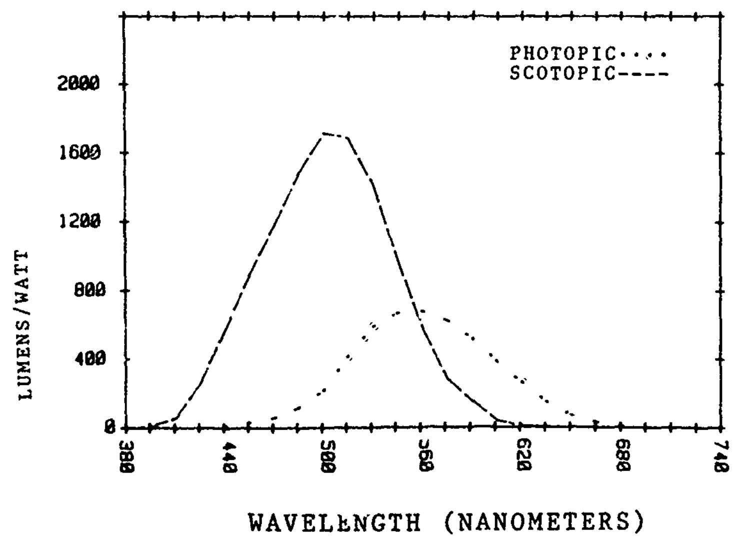

FIGURE 1
ABSOLUTE SPECTRAL AND ENERGY SENSITIVITIES OF THE UNAIDED EYE

The dynamic range of the photopic visual system is about 10^8 - 10 ML, and the dynamic range of the scotopic system is about 1- 10^{-6} ML. Although our eyes are very sensitive to light when fully dark adapted (under ideal conditions we can see a candle at a distance of about one mile), their resolution acuity is very low. At best, the scotopic visual system's resolution is about 20/200, and exhibits a central scotoma or blind spot. In other words, small objects will disappear when looked at directly.

First generation devices were photomultipliers that were sensitive to a spectral distribution similar to our eyes. They would amplify what visible light was available, and present the information on a monochromatic display. Since the display luminance was high enough to activate the photopic visual system, the limiting factor in resolution was the optoelectronics in the device rather than the eye.

The visual environment at night is relatively poor in visible wavelength energy, but remains relatively rich in longer wavelength (infrared) energy. Passive devices which used these infrared wavelengths could then rely on a statistically larger number of photons to activate the systems and improve resolution. The US Army's AN/PVS 5A second generation night vision goggles (GEN II NVGs) maintained sensitivity to the visible wavelengths, and extended their sensitivity to the near infrared wavelengths. This meant that the second generation devices could not only "see" light whose amplitude was normally too low for our unaided eyes to perceive, but they could also "see" wavelengths to which our retinas were insensitive, and improve resolution above that given by first generation systems. Figure 2 shows relative spectral sensitivities of the human eye and GEN II NVGs. It also shows the relative amounts of radiant energy available at night.

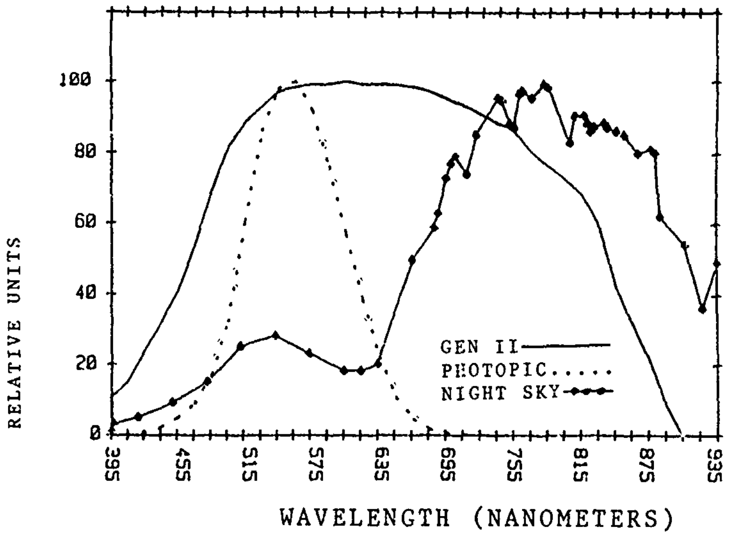

FIGURE 2
RELATIVE SPECTRAL SENSITIVITIES
OF EYE TO GEN II NVG

Scenes viewed through GEN II NVGs are perceived as shades of green because of the phosphor characteristics of the system. The output luminance of the NVGs is sufficient to activate the photopic visual system, but resolution is still limited by the NVGs rather than the eye. Typical visual acuities of individuals wearing operational units under typical night conditions range from 20/80 to 20/50. The unaided daytime visual acuities of these people are 20/20 or better. In addition, the instantaneous binocular field of view (BFOV) is limited to 40° rather than the 180° "unrestricted" field of view. Because of optical inconsistencies in the goggles, stereopsis (one component of depth perception) is poorer than expected for photopic vision, but equal to or better than that experienced with scotopic vision. Table 1 is a summary of various visual thresholds of the unaided eye and the visual system including NVGs.

Table 1

Comparison of Photopic, Scotopic, and NVG-Aided Vision

	Photopic System	Scotopic System	Eye + NVGs
Dynamic Range	10^{8} - 10 ML	1- 10^{-6} ML	10^{+8} - 10^{-8} ML
Receptor (Eye)	Cones	Rods	Rods & Cones
System Resolution	Better than 1 arc-min	10 arc-min	2-3 arc-min(NVG)
Spectral Sensitivity	350 - 700 NM	350 - 700 NM	AN/PVS-5: **** AN/PVS-6: ****
Max Spectral Sensitivity	555 NM	505 NM	AN/PVS-5: **** AN/PVS-6: ****
Perceived Spectral Output	Colors	Greys	Greens
Field of View	~ 180°	~ 180°	40°
Max Retinal Sensitivity	0° ± 2.5° (disc)	20°(annulus)	2.5° (disc)
Dark Adaptation Time (full)	10 minutes	30 minutes	Seconds
Dark Adaptation Time (flash)	Seconds	Seconds	Seconds
Dark Adaptation Time (failure)	-	-	Max 2 Minutes

AN/PVS 6 third-generation night vision goggles (GEN III NVGs) have reduced sensitivity to visible wavelengths, and greater sensitivity to longer wavelengths. The GEN III NVG output is also "brighter" than that of the GEN II, insuring the retina is adapted to a photopic level while viewing most scenes through the NVGs. Improvements in the optical system have also contributed to improvements in visual resolution while wearing the goggles, but considering wide variations in both the test method and the goggles themselves, best acuities appear to be in the range of 20/50 to 20/40. The field of view is still limited to 40°, and stereoacuity remains moderately good.

As we gained experience with NVGs in operational environments, several critical human engineering factors became apparent: cockpit (instrument, switch and display) lighting must be compatible with both the NVGs and the unaided eye if both are to be used to their fullest capability; the NVGs could be modified to improve field of view and display characteristics; refocussing from outside the cockpit to see instruments was a problem; new helmet mountings needed to be designed to better distribute the weight; and future NVG design must consider safety and ejection factors.

NVG COMPATIBLE LIGHTING

In order for NVGs to be most effective, the cockpit lighting must be optimized for the NVG's spectral sensitivity. Even low amounts of red and IR wavelengths generated within the cockpit can significantly reduce the goggles' sensitivity to the outside scene. Several vendors are now producing "NVG compatible" lights, even though there is no generally accepted measure of compatibility. The most promising products appear to be those that drastically reduce or eliminate emissions corresponding to visible red and longer wavelengths, however the absence of red warning lamps may be of some concern to traditional cockpit lighting engineers.

Our definintion of "NVG compatibility" contains two general criteria: 1) the lights will not degrade vision through the NVGs for specified lighting positions or configurations, and 2) the lights will allow good vision of instruments or other objects for the unaided eye. We include not only instrument and panel lights in this definition, but CRT and other displays.

Many users found that normal incandescent sources which were used to provide in-cockpit illumination for the unaided eye would emit too much infrared energy, and cause the NVG to lose sensitivity to out-of-cockpit scenes (because of activation of the automatic gain control). Many filtering systems, electroluminescent lighting schemes, and light emitting diode schemes were investigated; all of which were intended to reduce the emitted IR energy, and maintain sensitivity of the goggles.

We have found it helpful to describe at least three categories of cockpit lighting configurations, and have begun to establish compatibility ratios for most "NVG compatible sources" for each condition. Category 1 includes lights in the direct field of view of the goggles, category 2 includes light reflected from the windscreen or other object into the goggles, and category 3 includes "light pollution" from other sources. When viewing outside scenes, lights which are almost always in the direct field of view of the NVGs should not be considered to have the same effect as light sources normally well out of the NVG field of view.

We have developed a preliminary Compatibility Ratio (CR) that takes into consideration properties of both the unaided eye and the NVGs. This Compatibility Ratio may be used for any lighting configuration, type or placement, and will predict the relative effects of various vendors' products on visual and NVG performance. Essentially, CR is the ratio of the photopic eye response for a particular wavelength to the ANVIS sensitivity to the same wavelength.

Compatibility Ratio may be expressed mathematically as follows:

$$CR = \frac{\int_{400}^{700} V_\lambda \; N \; d_\lambda}{\int_{400}^{1000} G_R \; N \; d_\lambda}$$

Where:

V_λ = Relative photopic eye response for CIE 1931 standard observer

N = Relative spectral radiance for a particular light source (Watts/cm^2 Sr nm)

G_R = Relative ANVIS spectral response as measured or specified by manufacturer or JLC Ad Hoc Committee

Appropriate Compatibility Ratio limits are now being found by empirical determination for a subset of typical cockpit illuminators and categories. Spectroradiometric measurements of other illuminants will then allow ranking or compatibility comparisons of many cockpit lighting types and sources without the necessity of complex simulator devices. The CR will also provide suitable wavelength mixture information to lamp designers.

We are also in the process of defining spectral loci for acceptable NVG compatible cockpit lighting. Assuming the pilot will be able to see various instrument and cockpit indicator lights both with and without the NVGs, the problems of appropriate color coding, equality of hue and equality of luminance for either unaided or aided vision are added to the list of concerns for the illumination engineer. Care must be taken that warning and caution lights are sufficiently different from "normal" illuminants to avoid confusion. Historically, this has been accomplished via color coding the former lights red or yellow, but since these longer wavelengths are not compatible with NVG usage, the choice of spectral components is severely restricted.

NVGS AND VIDEO DISPLAYS

Initial tests indicate color video displays will have to be modified to reduce long wavelength emissions. Essentially, this means eliminating or significantly reducing the output of the red gun, with resultant degradation in visible color separation for the display graphics or symbology. In addition, displays using P-43 or similar phosphors will have to be filtered to reduce the normally tiny long wavelength "bump" on the emission curve. If this is not done, the display will cause the NVGs to lose sensitivity at brightness levels just barely sufficient for comfortable unaided vision.

One possible use of passive NVGs is in conjunction with active FLIR or other systems whose information is presented on a Heads Up Display (HUD). Since the HUD imagery is at optical infinity, refocussing the NVGs is eliminated. However, holographic or diffractive HUD combining glasses are tuned to reflect only the narrow green band of the P-43 phosphor. The imagery generated by these HUDs appears dimmer with AN/PVS 6 goggles than without! The reason for this apparent anomaly is the presence of a minus-blue objective lens coating, which prevents much of the green band from entering the NVGs.

DEPTH OF FOCUS PROBLEMS AND SOLUTIONS

The normal eye can accommodate or focus on objects at different optical distances. When we fixate on distant objects, near objects are blurred. When we change focus to the near object, the distant target is blurred. The range of distances over which we can see clearly without refocussing is called the "depth of focus" or "depth of field". Refocussing is accomplished by the action of the ciliary muscles in each of our eyes, changing the shape of the crystalline lens.

When properly adjusted, the ocular lenses of the night vision goggles place the image of the scene near optical infinity for the wearer's eyes. The NVG's objective lenses are then adjusted to focus on the object of regard. Because of their small f-number, there is very little depth of focus for NVGs. If a pilot had his system focussed for out-of-cockpit viewing, he would be unable to clearly see legends or instruments within the cockpit without manually refocussing each tube. After re ng his instruments, he must then refocus for clear distance viewing.

The AN/PVS 6 goggles were provided with an Aviator's Night VIsion System (ANVIS) mount, which allowed the pilot to look under the tubes to see his instruments. This feature attempted to eliminate the refocussing problem encountered with the AN/PVS 5 mounts, which were designed for ground use. Unfortunately, the ANVIS mount moved the center of gravity of the goggles farther from the head, and emphasized the problem of maintaining lighting compatibility for both the goggles and the unaided eyes at the same time. In addition, when the pilot wanted to see instruments near the top of his glare shield, the pilot needed to move his head in an uncomfortable manner to move the goggle tubes out of his field of view. Several other NVG manufacturers produced different systems to reduce the near vision problem, such as the Marconi Cats Eye, and the F&W Industries See-Through Night Vision Goggle (SNVS).

Another answer to the refocusing problem is addressed by shared-aperture optics. The concept of shared-aperture optics is similar to that of pinhole optics, in which light is imaged on a surface without the use of lenses. The shared-aperture concept is similar in that the objective lenses of the NVGs are coated with a minus-blue filter, effectively blocking short visible wavelengths of light. If cockpit lights are filtered or otherwise caused to emit only short wavelengths, these lights will not be seen when looking through the goggles. Now envision a small aperture, similar to that in a pinhole camera, in the minus blue coating. The relatively high energy, short-wavelength instrument light can pass through this aperture, and form a clear image in the NVGs. The large area around the aperture acts as a relatively low f-number optical system to the outside scene, which is rich in long wavelengths. With appropriate shared apertures, and with the system focussed for infinity, the pilot can see both the outside world and his instruments with relatively normal head and eye motions. Figure 4 diagrams the optical concept of shared apertures, which can be incorporated into present AN/PVS systems.

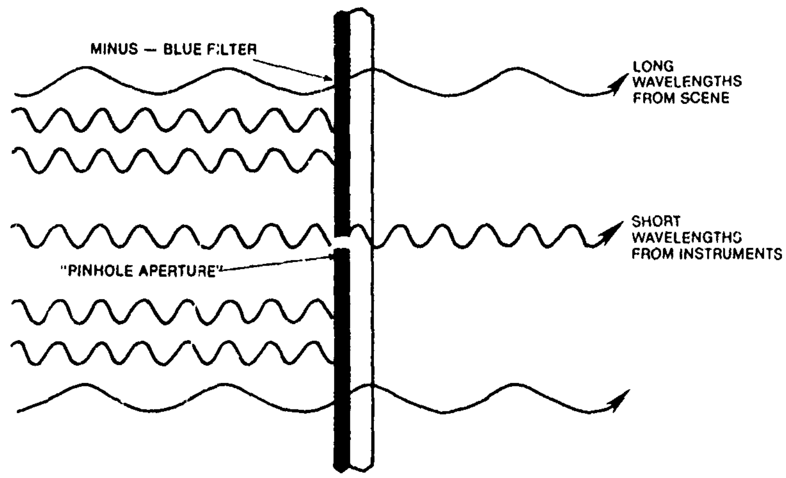

FIGURE 4
OPTICAL CONCEPTS OF SHARED APERTURES

One disadvantage of shared aperture optics is the critical selection of wavelengths suitable for in-cockpit illumination. These wavelengths must be almost totally blocked by the filter coating on the objective lens, thus significantly reducing the number of available illuminant choices.

FIXATION POINT PROBLEMS AND SOLUTION

Unfortunately, with any of the above methods of allowing vision of both the exterior scene and cockpit instrumentation, the pilot is still required to change his visual point of regard from outside to inside views; requiring changes in accommodation (for conventional aperture systems), light adaptation, and fixation posture. While his visual system is busy with one scene, important changes could be taking place in the other. Since NVGs are typically used at very low altitudes, normal aircraft velocities cause high rates of approach, and concurrent rapid changes in visual scene, which may degrade safety.

Scientists at AFAMRL approached the problem of seeing both the outside scene and instrument display by electronically and optically injecting critical flight instrument readings into the optical path of the NVGs. Now, the pilot need adjust his NVG's focus only once -- for distant viewing, and the flight data would also be seen near optical infinity, in the same field of regard as the outside scene. In effect, we created a Heads Up Display (HUD) for the NVGs, so we named it the AFAMRL NVG HUD.

Before using the NVG HUD, the visual duties of crew members of night flying aircraft were partitioned -- some tasked to look outside and others tasked to look only at instruments of various types. The pilot was to look outside the cockpit, while the co-pilot was to look at the critical instruments. Both the radar operator and copilot reported to the pilot verbally over the intercom. All crew members who were to look outside the cockpit wore night vision goggles, and the cockpit lighting was suitably modified to least interfere with the NVGs.

Since the development of the AFAMRL NVG HUD, the visual tasks of the crew can be partitioned in a more normal (i.e. more similar to daylight flying) fashion. The pilot's visual abilities are actually enhanced in that he can now see both the outside scene and flight data at the same time, without refocusing either his eyes or the NVGs. In fact, he need not change his visual regard from any exterior scene of interest; his flight data are projected to appear near the point at which he is looking.

The aircraft for which the NVG HUD was originally designed were not equipped with conventional HUDs, but displayed information on both video displays and round-dial instruments located on a conventional instrument panel. AFAMRL engineers were able to sample data on the computer bus serving the instruments, and use these data to generate a display on a small CRT. Several interactive studies were performed by AFAMRL and MAC to determine the optimum display format and symbology to effectively portray data values.

The CRT display was then coupled to a coherent fiber optics bundle, which was passed to the pilot's helmet. The output of the bundle was collimated and reflected from a beamsplitter or combining glass mounted on the NVG barrel, into the optical path of the

NVGs. In this fashion, the wearer of the NVGs could see the outside scene with both eyes, and the flight data image with one eye.

The brightness of the displayed data can be dimmed by the pilot, so he can "look through" the graphics at the outside scene, using binocular vision. As the need for critical flight data increases, he can increase the relative brightness of the graphics, so he can easily perceive the data with one eye. Since the other eye continually maintains a view of the out-of-cockpit scene, the visual system superimposes the imagery created on the face of the CRT over the outside scene. Since there is a great difference in appearance of the images, there is no retinal rivalry effect, and both the outside scene and the flight data are seen constantly. There have been no reports of the Pulfrich phenomenon while using the system, and no unusual lighting compatibility criteria need be addressed.

FIELD OF VIEW IMPROVEMENTS

Both the AN/PVS 5 and AN/PVS 6 NVGs restrict the wearer's instantaneous binocular field of view to a 40° circle. In order to carry on any visual search pattern, NVG wearers must increase the amount of head and neck motion to cover the same area previously covered by relatively simple eye movements alone. This increased head movement, combined with the weight distribution of the NVGs contributes greatly to neck muscle fatigue. Optically increasing the field of view of the NVGs results in a reduction of resolution. The pilot might see more in his instantaneous field of view, but what he does see will be less distinct.

One possible method of improving the horizontal field of view is "toeing-in" the NVG tubes. Since the NVGs have a magnification factor of 1, moving the tubes from their parallel position will have no effect on the positions of the eyes' lines of sight. Some time ago, AFAMRL produced a prototype NVG arrangement with the tubes "toed-in" 10° each. The result was an instantaneous field of view of 60°, consisting of a binocular overlapping field of view of 20°, and two monocular fields of view, each of 20° (See figure 5). All images in the instantaneous field of view maintain their correct relationships to all other images, and many pilots who tried the goggles were unaware of the presence of two monocular fields until told to alternate closing their eyes. The toe-in concept is not a new one ... it was patented in the US several years ago and is also demonstrated with Marconi's Cats Eye NVGs.

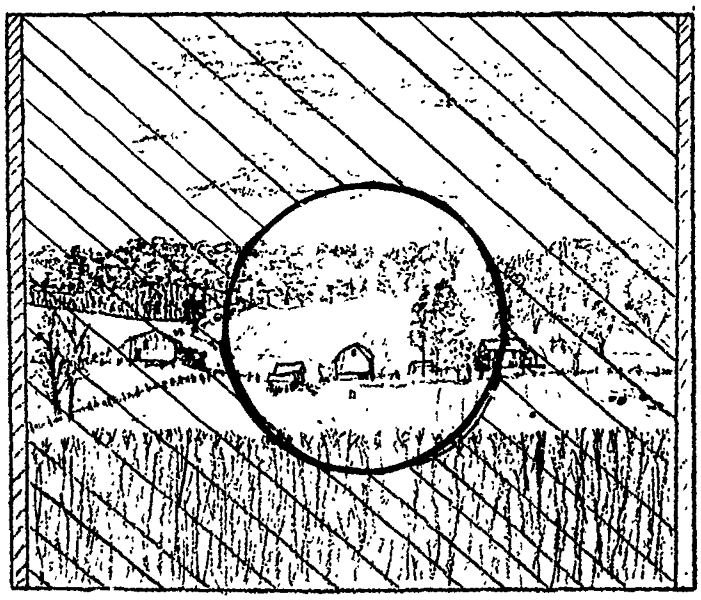

FIGURE 5A
CURRENT 40° FOV

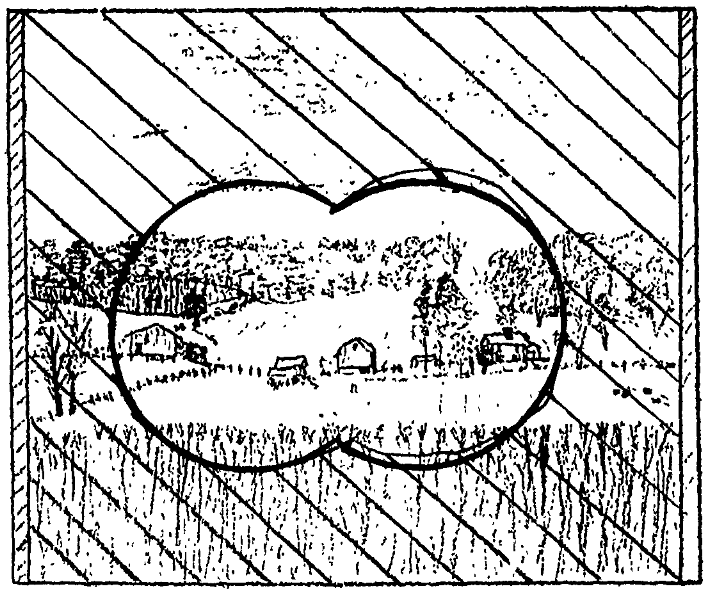

FIGURE 5B
AMRL MODIFIED FOV

FUTURE CONCEPTS

As display technology improves, and computer enhanced imagery matures, it is possible that the pilot of the future need not depend soley on his unaided vision while flying at night or under conditions of poor visibility. We see the early stages of new visual applications in the acceptance of NVGs, HUDs and FLIRs. The concept of providing enhanced imagery to the pilot is not new, but the methods to do this are rapidly evolving. AFAMRL is at the forefront of this technology with its state of the art Visually Coupled Airbourne Systems Simulator (VCASS), which allows the pilot to take advantage of new sensor technology by displaying various imagery on his helmet visor. Systems control, sensor pointing and device switching are performed with normal head and eye movements, providing a wide binocular field of view, with computer enhanced imagery, color and symbology. Artificially induced stereo cues add a new dimension to spatial sense.

The use of night vision enhancement devices appears to be growing in acceptance. Performance with these devices will be further aided by assuring appropriate human engineering factors are considered both in their design and application. It is not necessary to wait for next-generation improvements to become available in order to have an effective night vision system useable by aircraft pilots. NVG modifications and ancillary devices made and planned by AFAMRL and other organizations can be applied to today's second and third generation products.

MICRO-HEADS-UP DISPLAY FOR ENHANCEMENT OF NIGHT VISION GOGGLE OPERATIONS

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SUMMARY

A series of investigations which were initiated in 1976 and completed in March 1984 by the US Army Aeromedical Research Laboratory (USAARL) addressed the utility of providing a subminiature-heads-up flight instrument display for the NVG system. The research first attempted to identify critical flight information that should be provided to supplement the degraded environmental cues during NVG operations. Subsequent research explored methods of presentation (digital vs dynamic information), in-line mounting of the display to NVG, and in-flight human factor considerations of the total system. Since technology is rapidly changing this report does not reflect advances beyond these prototypes.

INTRODUCTION

Recent advances in the sophistication and flexibility of antiaircraft weapons force pilots to use terrain for cover and concealment, just as the foot soldier traditionally has. This neccesitates flight profiles which are dangerously close to the ground and trees. These flight profiles also are at slow speeds and the stability of the aircraft is reduced accordingly due to lack of wind streaming past the fuselage. The net effect is to increase pilot workload and reduce the amount of free time available to read instruments. Pilots flying nap-of-earth (NOE) in helicopters spend most of their time looking outside the aircraft in order to avoid obstacles, and relatively little time looking at instruments. When pilots use night vision goggles (NVGs) as aids to maintaining visual meteorological conditions (VMC) at night, the problem of instrument utilization becomes even worse due to degraded visual acuity and distance focusing problems. In addition, a helicopter pilot flying NOE while wearing NVGs may have goggle failure or enter ground fog (instrument meteorological conditions or IMC) and unexpectedly be required to change from VMC to IMC. This requires pilots to refocus their vision and attention into the aircraft and onto their instruments, a task complicated by the NVGs.

A heads-up display (HUD) is a device used to provide vehicle status information to operators while their gaze is fixed outside the vehicle (Walchi, 1967). HUDs have been used primarily in fixed wing aircraft and originally were used as gunsights. Generally, information (either symbolic or numerical) is presented to the operator (pilot) by means of a collimator and combiner lens in order that the information appears focused at infinity outside the aircraft.

HUDs have been tested in helicopter operations but have not until recently been well received (Astronautics Corporation of America, 1974; Ketchel and Jenney, 1968; Poston and DeBellis, 1975). In the fixed wing aircraft, most attention is directed along the line of flight; while in a helicopter, attention can be focused in virtually any direction. Helicopter pilots must redirect their attention from the object(s) being observed into the HUD. Apparently, once the decision is made to reorient the head and gaze, the location of the new focus point does not matter. As a result, HUDs have been developed for helicopters which provide collimating optics and symbol generators mounted directly on the pilot's helmet. As the pilot turns his head, the HUD moves with him. This technology is currently in use in the AAH-64A "Apache" attack helicopter. While helmet-mounted HUDs show promise for some NVG applications, at the time of this work there were none compatible with NVGs. For instance, night viewing in the AAH-64A is accomplished by an infrared imaging system slaved to the pilot's head movements and displayed via the HUD.

Bell Helicopter-Textron, Inc., under contract with the US Army, experimented with high-risk, high-payoff HUD technology to be used in conjunction with NVGs. The feasibility of displaying three-digit, seven-segment numbers to pilots wearing NVGs has been demonstrated. This technology used miniature (approximately 1.5 mm) mirrors mounted on a clear glass lens to reflect the image of segmental light-emitting diodes (LEDs) directly through the pupil to the retina of the pilot's eye. This phase of the concept development utilized the LED digital displays to provide helicopter airspeed, altitude, and heading information. Previous research (Simmons, 1978) demonstrated that the assessment of visual workload of helicopter pilots would predict that airspeed information comprised only 14% of pilot's total visual requirement. Altitude information comprised 12% and heading 20%. However, pitch and roll information from the aircraft's attitude indicator during normal instrument flight was required 35% of the total visual workload time. This demand for attitude information increased with less stable maneuvers (instrument takeoff and slow flight) to as high as 45%. Based on this information, it was ascertained that the need for attitude information was twice as important as other visual information available to the pilot.

Personal inquiry at the US Army Safety Center and conversation with their investigative personnel identified inadvertent IFR, spatial disorientation, and even battery failure as possible contributing factors to accidents during night vision goggles operation. Combined with the results from the research data that attitude information has high visual priority and with the added capability of providing dynamic displays during NVG operations, additional research to determine the effectiveness of adding attitude information to the goggles became essential.

Thus, the last phase of the heads-up display concept was originated to provide not only airspeed, altitude, and heading information but also dynamic pitch, roll, and trim information. This complete heads-up presentation conceptually provided the pilot about 90% of all visual information required to fly. Since this flight information was deemed critical to efficient helicopter flight and the concept of enhanced flight capability had been demonstrated by the utilization of miniature heads-up displays, the development of a display encompassing the feature of the prototype (i.e., lightweight, pilot acceptable, etc) would further enhance pilot capability during NVG flight operations. A display such as this would provide supplementary information to those cues externally seen but often degraded through the goggles as well as provide an emergency heads-up instrument display capable of independently fulfilling the pilot's visual needs for safe flight. Bell Helicopter-Textron, Inc.. under contract with Naval Air Systems Command (NAVAIRSYSCOM) prototyped such a dynamic display system based on the concept of a spectacle mounted micro-HUD which would be compatible with the AN/AVS-6 (ANVIS) NVG. The US Army Aeromedical Research Laboratory (USAARL) and the Directorate of Combat Developments (DCD), US Army Aviation Center agreed to evaluate the feasibility of the micro-HUD and determine in-flight utility.

METHOD

Subjects

Twenty subject pilots wore the micro-HUD during simulated IFR flights. Ten subject pilots wore the micro-HUD during NVG VFR flights in USAARL's JUH-1H helicopter.

Apparatus

The Bell Helicopter-Textron micro-HUD consists of a pair of adjustable spectacles, numeric symbol generator, dynamic attitude generator and a custom microcomputer flight box (Figure 1). The microcomputer flight box is an electronics module which utilizes an 8085 microprocessor CPU and ROM/RAM memory. The unit measures 25 cm X 20 cm X 15 cm and weighs approximately 4.5 kg. The unit uses as input electrical signals which are taken from either aircraft instruments or redundant instruments mounted in the aircraft especially for that purpose. A more indepth description of the electronic specifications and system operator can be found in USAARL Letter Report #84-5-3-4.

Spectacles

The symbol generators and optical system are mounted on a modified pair of safety glasses. The frames are modified such that interpupillary distance is adjustable from the midline for each eye. That is, both the left and right lens move to insure that the midline of the lens is located on the midline of its respective eye. The nosepiece of the glasses is adjustable in the vertical plane to allow the horizontal midline to be adjusted to the height of the eye's pupil (or lens). As one eye usually is higher than the other, the left eye system is fit utilizing these adjustment mechanisms. The right eye pupil height is accommodated by utilization of a set of replacement lens for the right eye of the spectacles. These lens have mirrors set at varied, predetermined heights to offer a full range of right eye heights. The left lens has mounted on it four aspheric mirrors at 6.25 mm from the center, one at each of the following positions: 12, 3, 6 and 9 o'clock. The right lens has a single aspheric mirror mounted so as to project directly into the center of the pilot's field of view. The spectacles are held firmly in position by means of cable-type earpieces and an elastic/velcro headband.

Numeric symbol generator

The left eye system (Figure 2) presents only numeric information. This information takes the form of four, three-digit numbers formed by seven-segment LEDs. The information presented is heading at 12 o'clock, altitude at 3 o'clock, slip at 6 o'clock, and airspeed at 9 o'clock. Each set of LEDs shines upon a prism in the generator which directs the image onto the proper aspheric mirror of the spectacle lens. The mirrors then direct the image through the cornea and pupil and onto the retina of the eye.

Dynamic attitude generator

The right eye system (Figure 3) uses a unique symbol generator system to allow a dynamic pictorial representation of pitch and roll. This system projects an image which subtends approximately 6 degrees of arc in the center of foveal vision. It is capable of projecting 128 rows and 128 columns of discrete points for a total of 16,384 programmable points. These points are used to draw symbols and text in the same fashion that some football scoreboards draw pictures.

The dynamic attitude generator presents austere pitch and roll information (Figure 4) to the pilot. The term austere is used to denote that the normal amount of information associated with pitch and roll is not presented. Roll information consists

of a straight line used to represent either the attitude of the blades or the attitude of the horizon depending upon initial setup. While zero roll marks are provided, pilots are required to estimate the degree of roll by looking at a line which moves in a one-to-one correspondence with the real world. The pitch information is provided by means of a fixed, minimal pitch ladder which provides 5 and 10 degree pitch up and down marks. The roll reference line always cuts the pitch ladder precisely in the middle and pitch is read at this point. The symbology utilized is graphically presented (including left eye system) in Figure 4.

Switch selectable options

Update rates (how often information changes on the display) are switch selectable. The rates available are one, two, three, and four times a second. The left eye numeric system can be disabled and the information then is presented at the edges of the dynamic attitude display (right eye) utilizing dot matrix number formulation. The symbology of the attitude indicator can be changed to one incorporating a full pitch ladder. In this format, the austere pitch ladder shown in Figure 4 expands to cover approximately half of the possible display area. This pitch ladder is fixed and has a fixed aircraft symbol drawn in the center. The pitch/roll line moves in this version precisely as it does in the austere version.

The signal conditioning box developed by USAARL to provide the type of signal required by the flight box also is capable of changing information or mode of operation via switches. Altimeter and airspeed information is switch selectable between barometric and radar operation.

PROCEDURE

Fitting

Due to the adjustable nature of the spectacles, custom fitting was required to insure that all symbology was visible. Experienced personnel could complete a fitting in 15 minutes, although it occasionally took 45 minutes. A certain number of prospective subjects could not be fitted. This was estimated to be about one in 10 and appeared to be due to an asymmetry of the ears, one ear being higher than the other. This would cause a tilt in the lens which would throw one or more of the projected images outside of the pupil. Even for those who could be fit properly, moving the facial muscles, as in squinting, could cause the images to disappear. The symbol generators sometimes conflicted with the SPH4 helmets, especially when a subject's head size was close to the upper limit of the helmet size. In these cases, a modified helmet was issued and worn.

Simulated IFR Flight

USAARL's helicopter instrument procedures trainer was modified to provide appropriate signals and was used to simulate 1-hour IFR flights. Seven of the subjects also wore the ANVIS NVG while the three remaining subjects wore just the micro-HUD since ANVIS was not available. The flight profile consisted of instrument takeoffs, turns, descents, cruise flight, and instrument landing system (ILS) approaches. The cockpit was illuminated with blue-green light for ANVIS compatibility. The last 10 minutes of the flight were conducted with all instrument lights off so that all flight information came via the micro-HUD.

ANVIS NVG Flights

Subjects were fitted with the micro-HUD at USAARL and then reported to Cairns Army Airfield. After preflight preparations, the micro-HUD again was fitted to the subject and the safety pilot flew to either USAARL's research stagefield, High Falls, or to Ech stagefield. The choice of stagefield was determined by the subject's qualifications, availability of stagefield, and availability of and NVG IP. Due to the lack of emergency crews, flights at High Falls consisted of traffic pattern work, cruise flight, and hover work. Flights at Ech included all of the profiles flown at High Falls as well as running landings, autorotations, slope landings, and NOE flights.

RESULTS

Compatibility with AN/AVS-6 (ANVIS)

The ANVIS is a third-generation light-amplifiction device which is helmet mounted. When in use, it is positioned in front of the pilot's eyes. The micro-HUD was designed to fit under the ANVIS and, in fact, is perfectly compatible with the ANVIS (Figure 5).

Comfort and Fit

Subjects generally were easy to fit with the micro-HUD as indicated above. On occasion, the nosepiece vertical adjustment screw would extend to the point that the helmet liner rested on it, transferring weight and vibration through the spectacles to the nose. When this occurred, a slight readjustment to the helmet eliminated the problem.

The fit of the micro-HUD was sensitive to minor movement in that only .5 mm of movement of a mirror was sufficient to make the image disappear. This required that the micro-HUD be held firmly in position by velcro/elastic straps. As would be expected,

this arrangement caused discomfort. As stated, occasional problems were found with the micro-HUD contacting the helmet, which was resolved by changing helmets.

Visibility of Symbology

The viewing ends of the ANVIS tubes can be seen as miniature television screens and emit light which forms the images. The micro-HUD must be viewed against this green background and, therefore, must be of sufficient intensity to be seen against the ANVIS background. All subjects reported that the micro-HUD was visible against the background of the ANVIS tubes. However, even at the brightest intensity setting, most subjects desired greater contrast between the red numbers and dots of the micro-HUD and the green ANVIS background. When worn without the ANVIS, the micro-HUD was seen easily against the dark night sky. If the symbology happened to be positioned by head movement over the instrument panel or a town, then the image was difficult to read. Some subjects expressed concern that the images might cause difficulty when trying to locate a target on the ground. They suggested that a cut-off switch be built in to allow easy elimination of symbology when required.

The right eye dynamic symbology was easiest to fit and remained visible at all times because it projected into the center of the field of view. Some subjects in flight had occasional problems seeing the left eye display which was corrected by shifting the glasses on the face or, occasionally, by tightening a loose adjusting screw on the glasses.

Utility of Symbology

The primary emphasis of this evaluation was the feasibility and utility of the dynamic right eye attitude display. Subjects accepted it as an indicator of aircraft attitude after about 1 hour of use. Most subjects complained about the lack of specific degree of roll marks; however, they rapidly learned to do without them. The usual procedure when subjects complained was to have the safety pilot call out degree of roll until a standard rate turn had been established. This linked the aircraft feel and the knowledge of what constituted a standard rate indication with recollections of how the horizon line in the standard instrument display looked. Pitch indication was readily accepted despite the display not translating axis as a normal indicator does. In fact, no one seemed to notice or perhaps consider worth mentioning this aspect. There was some consternation in regard to the direction in which pitch was indicated. Most pilots preferred the pitch indication follow that of the standard pitch display. While reversing the direction was a trivial change, pitch indication was left as initially set up throughout the study.

The micro-HUD, when used in the simulator, displayed roll in the traditional "inside-out" format. That is, the roll line moved in a one-to-one fashion with the horizon line in the attitude indicator. When used in the aircraft, the display used the "outside-in" format, or reflected the attitude of the aircraft as would be seen by an outside observer. The subjects who wore the micro-HUD in both situations noticed the difference and were able to adapt to the change although they preferred that the display move in unison with the aircraft roll display. It should be noted that while pilots liked the alternate full pitch ladder format, they felt that it was too cluttered and caused difficulty when focusing on specific objects.

The left eye digital displays required some training to use but were easy to use after about an hour. The optics of that system were designed so rotations of the eye were required to focus attention on specific information. This served two purposes. First, information was outside of the instantaneous field of view. This left a relatively uncluttered view when looking straight ahead although the presence of the information was noticed through peripheral vision. Second, as the eye rotated toward any one piece of information, other undesired information disappeared because the pupil of the eye was out of position for the other mirrors to focus on the retina. Most of the training time was required to train the eye where to go for the information so that it could be acquired at a glance instead of after searching the scene for its location.

The most desired information was heading. Subjects reported that it was useful when hovering, in unfamiliar traffic patterns, and during NOE flight. The least desired information was yaw. It was felt that a display indicating only one ball out of trim or in trim was too insensitive. For test purposes, the indicator was recalibrated to indicate out of trim at the half-ball position. Airspeed and heading information were accepted without comment, with the exception that altitudes in excess of 1,000 feet (either barometric or radar) caused a flashing 999 to appear and subjects expressed preference for a fourth digit.

DISCUSSION

The original AN/PVS-5 NVGs totally enclosed the face, and viewing of any aircraft instrumentation or outside scene was through the tubes only. Under these conditions, IMC or tube failure was likely to be catastrophic as recovery procedures could not be initiated until the NVGs had been removed. This was the original impetus for development of the NVG HUD. This problem has been eliminated largely by the recent modifications to the AN/PVS-5s (McLean, 1982) and the introduction of the AN/AVS-6 (ANVIS) which allows under and around viewing of the instrument panel. As indicated above, in some situations the micro-HUD was considered to be very useful. These instances were always situations where flight instrumentation was required, such as hovering, during NOE and in the

traffic pattern. The testing done for this report may not have placed the micro-HUD in situations in which its utility during high information demand situations could be assessed.

Negative Aspects of the HUD

The most noticeable problem in the dynamic attitude display is "jitter." Jitter is generally considered to be small vibration in a display's image which causes blurring or illegibility. Helicopters vibrate. At some times the vibration is minimal; at other times it is quite severe. The micro-HUD dynamic display is based upon a short piece of fiber optic material which is caused to oscillate in the vertical plane at its natural resonant frequency. In the micro-HUD tested, this oscillation was under minimal control and the speed of travel and distance traveled could vary from moment to moment. This oscillation was often out of synchrony with the aircraft and the pilot's eye oscillation. The result was that if both aircraft and eye were traveling in the same direction, perceived vertical movement was minimized. If the two were traveling in different directions, perceived vertical movement was maximized. This phenomenon was apparent especially at the bottom of the display. This was because the decision, as to when the moving fiber optic had reached its proper vertical position for a particular row, was based solely upon elapsed time since tripping an optical sensor. The assumption that time is in one-to-one correspondence with vertical displacement is true only in a situation without vibration. The result was that the numerics, when switch selected to be displayed on the dynamic attitude indicator, could only be clearly read in the 12 o'clock position. Those in the 3 and 9 o'clock positions could be read sometimes, depending upon aircraft vibration; and the one in the 6 o'clock position was illegible. The left eye projection system did not have a jitter problem. Another problem with the dynamic attitude indicator was that it occupied a small area of view (6 degrees of arc subtended). The 16,000 points available provided resolution beyond that which could be discerned in flight. In fact, testing was delayed while the display was reprogrammed to maximally utilize all available space. (Pitch markings produced in the original layout were found to be too small to be perceived under condition of jitter.) Any textual material used in the dynamic attitude indicator would have to be displayed with oversized letters and rapidly would use up available space as well as cluttering the instantaneous field of view.

A third problem noted that minor movement in the spectacles caused the left eye system (digital information) to lose some numbers. Squinting or other facial movements sometimes were sufficient to cause loss of image. This could be overcome by moving the images closer to the instantaneous field of view, but only at the cost of cluttering the display. Also, the micro-HUD spectacles had to be kept stationary on the head. A velcro/elastic band similar to a sports retainer for glasses was used to stabilize the display. Often this was uncomfortable as the helmet headband had a tendency to pull the strap down and tighten as the helmet was put on. The discomfort aspect probably outweighed the stability aspect after an hour or so.

A fourth problem encountered was that the information displayed on the micro-HUD was instantaneous and was not "dampened" at all. Most displays in aircraft do not have the capability of following rapid aircraft changes. They have lags in the responsiveness which tend to eliminate large, fast changes and present smoothed trends. The micro-HUD would sample the aircraft status and present instantaneous information. This transferred the work of trend estimation to the pilot and often left the pilot trying to integrate rapidly changing numbers into a coherent picture of what the aircraft was going to do. A better situation would be one in which the display moved smoothly, without sudden jumps, and indicated current "average" status. Along these lines, subjects uniformly selected the slowest update rate available (once per second) to minimize the rapid changes being seen.

Positive Aspects of the Micro-HUD

While there are undeniable technical problems with the micro-HUD and certain symbology features which could be improved, it must be recognized that, for the most part, the micro-HUD worked successfully. It might not be as comfortable, stable or bright as desired but it was able to present the instrumentation as planned and was used successfully to fly a ground controlled approach with NVG off. It also functioned as desired during the one NVG failure experienced in flight. Most of the problems identified are amenable to solution in a next generation effort. The micro-HUD appears to reduce workload during instrument-dependent maneuvers and was generally regarded by subjects as labor saving at those specific times.

Proposed Improvements to Micro-HUD

The micro-HUD, as configured currently, is not bright enough to be used during daylight hours and is only marginally bright enough at night. This situation might be improved by changing the basic timing circuitry so that instead of writing information (turning LEDs on) only on the downswing of the fiber optic oscillation cycle, information is written on the upswing as well. This would immediately double the intensity without changing the LEDs or optics system.

The spectacle mount system could be dropped in favor of system clipped directly to the ANVIS tube. This would eliminate most fitting problems, discomfort, and interactions with facial musculature. Only an ounce or so would be added to the ANVIS and probably would not be noticed. It also would eliminate the need for personalized mounting glasses

and maintenance problems due to hardware interchanges. However, this would eliminate the stand-alone capability of the HUD which may prove to be desirable if intensity problems are overcome.

The dynamic display needs to be stabilized against jitter by addition of position feedback and an improved cycle control system. As configured, the fiber optic bundle oscillates with only minimal control. Technology exists which should be able to compensate for vibration induced changes.

The size of the image should be expanded. This probably is a function of the mirror reflection system and not the display itself. Experimentation with different shapes and sizes of mirrors should be done in a systematic fashion. An optical physicist might be able to design an appropriate system to accomplish this work.

Uses for the Micro-HUD

As mentioned above, the micro-HUD is a device used to provide aircraft instrumentation when using the ANVIS. The aircraft used for testing (JUH-1H) and the profiles flown have a low demand for aircraft status. Within the context of this scenario, the micro-HUD proved to have marginal utility. Other aircraft and other scenarios do have explicit needs for information while looking outside the aircraft. For instance, picking up a sling load while wearing NVGs requires the pilot to hover (a head-up maneuver) while attempting to maneuver over and down onto a ground load. Without external lights for the ground crews, their ability to feed back information to the pilot is severely limited. Addition of sensing devices to present on the micro-HUD the relative locations of the aircraft hook and ground load may simplify and make safer a tricky and frequent operation. Fixed wing aircraft landing with NVGs and no lights could benefit by the addition of a micro-HUD providing airspeed, attitude, angle of descent, etc. This information is especially critical in landing on short, unimproved fields which often have obstacles in the immediate area.

A highly probable use for the micro-HUD is in the area of weapon systems. One possible scenario is that of an AH-1S Cobra TOW attack helicopter attempting a pop-up and fire sequence at an armored target. The pilot could benefit by using the micro-HUD to provide aircraft attitude, heading and power settings as he comes into and holds firing position. The copilot could benefit by using this system in conjunction with the telescopic sight system (TSU) to provide weapon system status and other required information without visually coming out of the TSU.

CONCLUSIONS

The limited utility in the VFR flight profiles tested should not be construed as a failure of the micro-HUD. As long as aircraft status information is required, the micro-HUD will be useful. In instances where information was specifically required (e.g., heading while NOE or attitude during a vertical helicopter instrument recovery procedure), the HUD was used and appreciated. As always, careful consideration of the flight profile and the predominance of required information must be considered when determining the utility of any HUD.

The laboratory and inflight evaluations of the micro-HUD described here demonstrated both the feasibility and utility of such a device for selected mission scenarios. Although man-interface problems were discovered using the prototype, these difficulties can be overcome with future engineering development. These efforts are continuing as a result of interest within the aviation industrial community.

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Figure 1. Bell Helicopter-Textron Night Vision Goggle Micro-Heads-Up Display. From left to right: Spare lens/mirrors, spectacles with symbology projectors, nosepieces, microcomputer flight box, tools.

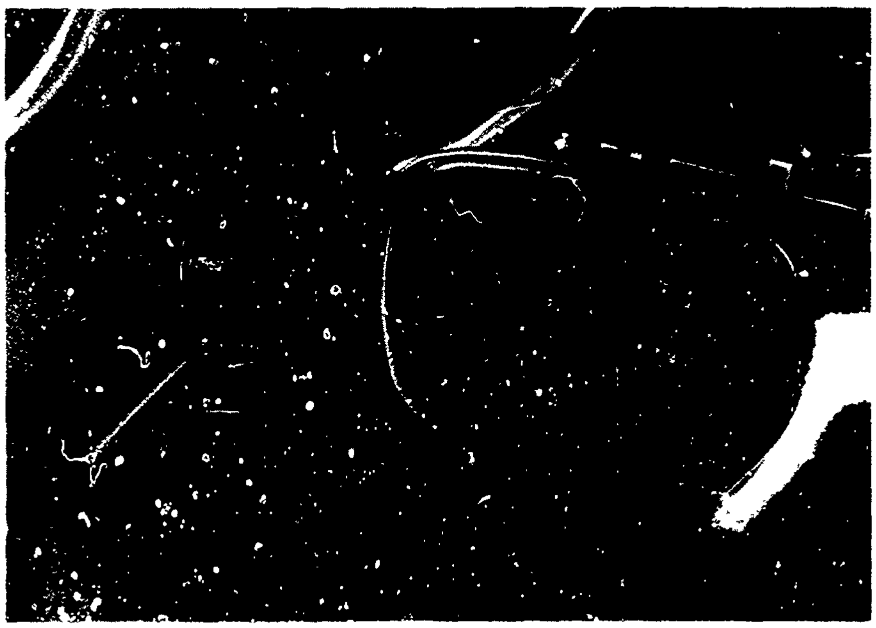

Figure 2. Left eye numeric generator. On the left, bow mounted projector. Notice the four aspheric mirrors mounted on lens.

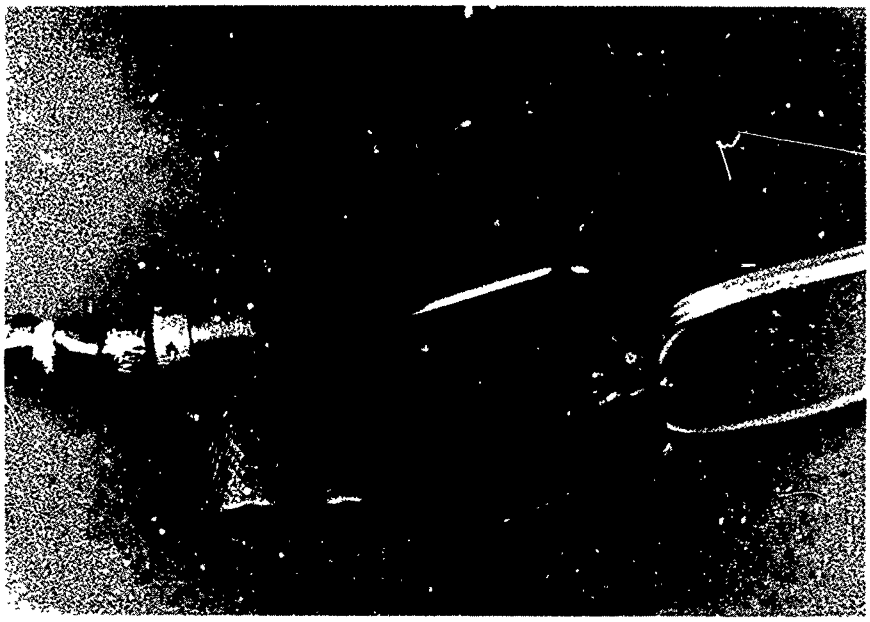

Figure 3. Right eye dynamic attitude generator. Vertical adjustment and focus is accomplished by means of adjusting screws at lower left. The image is available at an opening at the right of the projector (next to lens).

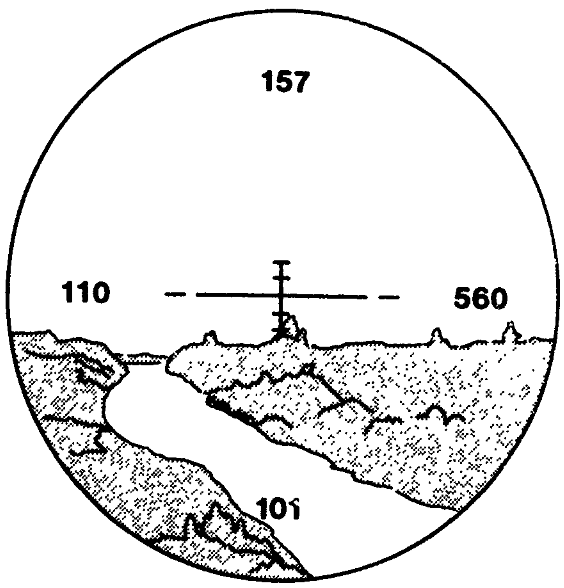

Figure 4. Artist's concept of austere micro-HUD symbology. Heading is at 12 o'clock, airspeed at 9 o'clock, altitude at 3 o'clock, and slip at 6 o'clock. The zero in the slip indication represents the position of the slip ball.

Figure 5. Micro-HUD worn under the AN/AVS-6 ANVIS NVG

AEROMEDICAL LESSONS LEARNED WITH NIGHT VISION DEVICES

by
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SUMMARY

This paper presents a review of night vision devices used in the military helicopter flight environment, and aeromedical lessons learned. Discussion revolves around experience with three U.S. Army aviation systems: the currently used second-generation night vision goggle (NVG), or AN/PVS-5; the soon-to-be-fielded AN/AVS-6 third-generation NVG; and the AH-64 Apache thermal sensor and imaging system. Performance characteristics are presented, and primary emphasis is on aeromedical research related to pilot interface with the systems to include visual acuity, contrast sensitivity, depth discrimination, dark adaptation, crew fatigue, and adaptational problems.

BACKGROUND

Night vision goggle technology began in World War II with infrared (IR) sniper scopes. These systems required an IR searchlight to provide sufficient energy to produce a usable picture. At the end of the war, a fighter aircraft was landed at night on an aircraft carrier using a prototype binocular IR goggle with low-level IR deck lights. In Vietnam, the first generation of Starlight scopes was used effectively. This technology, unlike its predecessors, provided amplification of radiant energy reflected from objects by the moon and stars.

The second-generation NVGs were made smaller and lighter mainly by using the microchannel plate described by Major Robert Verona in his paper titled "Image Intensifiers: Past and Present." These also incorporated circuitry to limit the gain when exposed to bright lights, without shutting the goggles down. The first U.S. prototype binocular goggle version, the SU-50, was used in some rescue attempts and special operations in Vietnam. The first U.S. production goggle, the AN/PVS-5, was intended for ground use. Army aviation adopted this goggle in the mid-70s as an interim measure until an aviator version of third-generation NVGs could be fielded.

Major improvements from second- to third-generation image intensifier tubes include improved resolution, greater sensitivity in the near-infrared spectrum, longer tube life, and less weight.

NIGHT VISION DEVICE PERFORMANCE CHARACTERISTICS

This discussion will focus upon the three fully developed U.S. night vision systems: two image intensification systems (the second- and third-generation NVGs), and the thermal sensing and imaging system developed for the AH-64 Apache helicopter.

The AN/PVS-5s use second-generation tubes. As discussed below, the faceplate of the AN/PVS-5 was modified and approved for aviation use in 1982, providing unaided look-under and look-to-the-side capability and compatibility with spectacles. Both the AN/PVS-5 and the modified version are shown in Figure 1. The typical visual characteristics of second-generation NVGs are maximum resolution equivalent to 20/50 visual acuity, 40-degree circular field-of-view, and monochromatic vision.

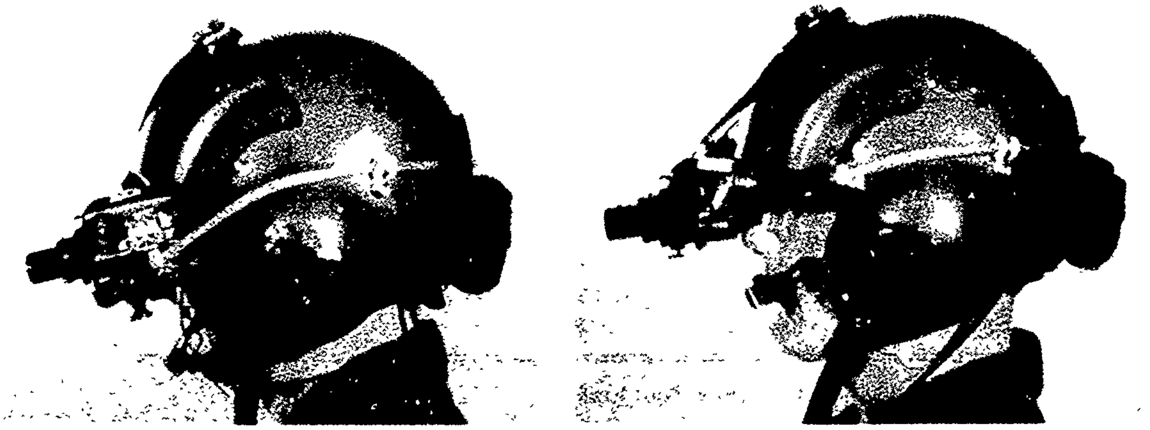

Figure 1. Photos of the AN/PVS NVG: at left unmodified and at right with modified faceplate.

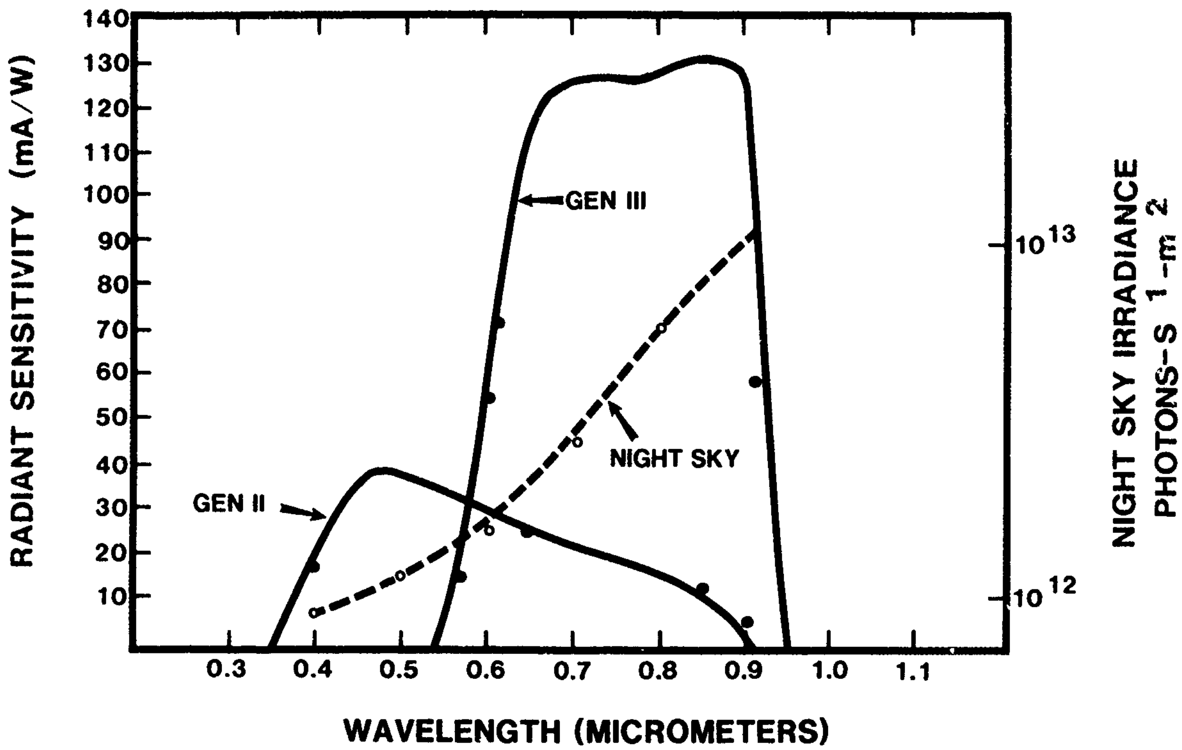

Figure 2. Comparison of sensitivities between GEN II and GEN III photocathodes.

The photocathode of second-generation tubes is sensitive to electromagnetic energy from .400 to .900 microns (Figure 2). However, it should be noted that what is presented to the eye is the image of the phosphor screen. In this case, the image is a fairly narrow band of luminance in the yellow-green portion of the human visual spectrum that peaks at about .560 microns. The intensity of this image (typically ~ 2-3 footlamberts mean luminance) falls within the mesopic/low photopic range where only the rods and more sensitive cones are responding (See Table I).

TABLE I

SCALE OF LUMINANCE LEVELS FOR TYPICAL STIMULI
(millilamberts*)

	10^{10}	
Sun's surface at noon	10^{9}	Damaging to retina
	10^{8}	
	10^{7}	
Tungsten filament	10^{6}	
	10^{5}	
White paper in bright light	10^{4}	
	10^{3}	Photopic (colored vision)
Comfortable reading	10^{2}	↑
	10^{1}	
	10^{0}	
	10^{-1}	Mesopic
White paper in moonlight	10^{-2}	
•Cone threshold	10^{-3}	↓
White paper in starlight	10^{-4}	Scotopic (colorless vision)
	10^{-5}	
•Absolute rod threshold	10^{-6}	

* 1 millilambert = .929 footlambert

(Adapted from Rubin, M. L., and Walls, G. L., Fundamentals of Visual Science, Springfield, IL: Charles C. Thomas, Publisher, 1972, p. 40.)

The AN/AVS-6 is called the Aviator Night Vision Imaging System (ANVIS) and uses third-generation tubes, a dual battery pack, and a 10 G binocular assembly separation feature (Figure 3). The assembly is mounted to provide look-under capability much the same as the modified AN/PVS-5. The field-of-view is the same as the second-generation goggles. They are sensitive to spectral energy in the .550 to .950 micron range; and, as noted in Figure 2, their sensitivity is greater, particularly in the near-IR portion of the electromagnetic spectrum where night sky irradiance increases. The phosphor image to the eye has a resolution equivalent to 20/40 visual acuity, presented as a fairly narrow band peaking at .560 microns on the visual spectrum. The intensity or brightness of the image is slightly higher than that of the AN/PVS-5, but still within the mesopic/photopic range of the human eye.

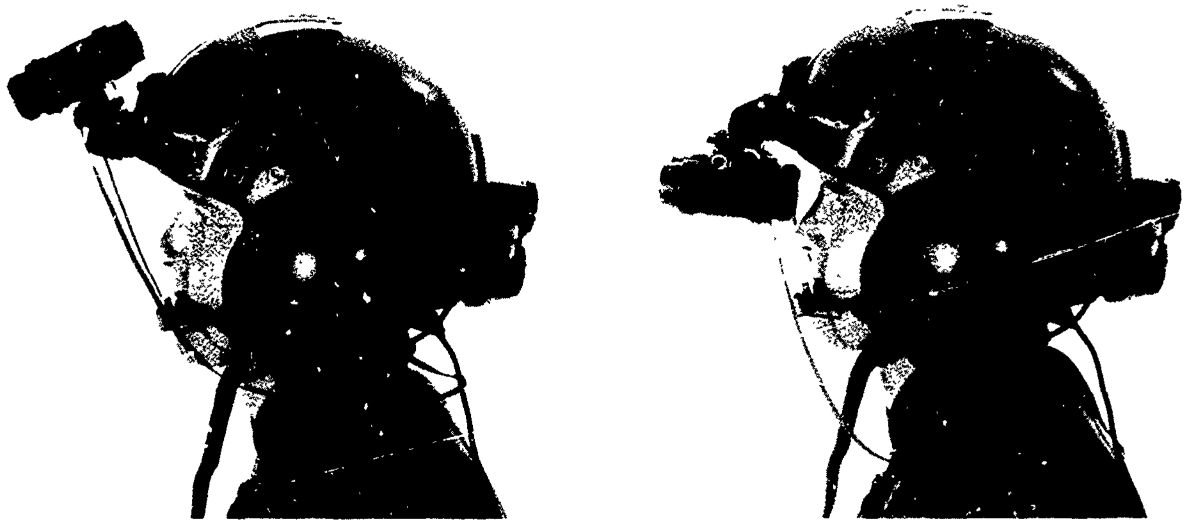

Figure 3. AN/AVS-6, also known as the Aviator Night Vision Imaging System (ANVIS).

The AH-64 Apache system uses a thermal (far IR) radiation sensing component on the nose of the aircraft known as the Pilot Night Vision System (PNVS); and an integrated helmet and display sighting system (IHADSS) which presents the processed image to the pilot and copilot (Figure 4). More complex and expensive than image intensification systems such as NVGs, this system "sees" in darkness and foul weather by displaying a visual image of the very small temperature differences between a target and its background. The PNVS-generated image is displayed on a one-inch diameter cathode ray tube within the IHADSS, which then optically magnifies the image and reflects it from a small beam splitter or combiner lens located before the right eye.

The IR sensor, located on the nose of the aircraft, is slaved to the pilot's head motion and has a maximum slew rate of 120 degrees per second. The display field-of-view is controlled by the pilot's line of sight and can be selected from a field-of-regard of ±90 degrees azimuth and +40 to -70 degrees elevation. Spectral sensitivity for the PNVS is in the .75 to 1.2 micron range.

The IHADSS image presented to the pilot has a resolution similar to that of third-generation NVGs, equivalent to approximately 20/40 visual acuity (VA). The display field-of-view is 40 degrees horizontally and 30 degrees vertically, providing a one-to-one video image overlay of the real world. The image, from the cathode ray tube phosphor screen, in this case is a very narrow band at .543 microns. The intensity (or highlight luminance capability) of this image is 0.3 to 150 foot-lamberts. The pilot can adjust the brightness or intensity.

The IHADSS also provides on-call flight information symbology to the pilot, including attitude, heading, altimeter (radar), airspeed, and engine torque. Often this symbology is used without the PNVS imagery during daylight flight, allowing the pilot to look through the beam splitter with the right eye in visual meteorologic conditions. The AH-64's Target Acquisition and Designation System (TADS), available on call, uses the same sensor technology as the PNVS. This system normally is operated by the copilot/gunner, independently of the PNVS.

Most of the performance characteristics of the night vision devices just presented are summarized in Table II.

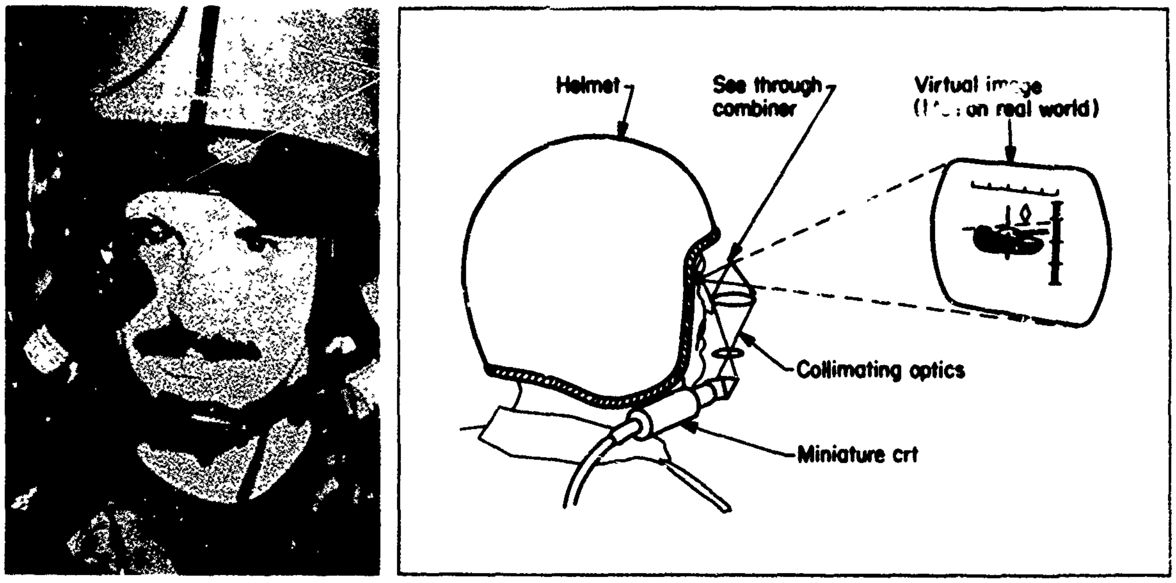

Figure 4. Photo and diagrammatic sketch of the Integrated Helmet and Display Sighting System (IHADSS).

TABLE II
SUMMARY OF PERFORMANCE CHARACTERISTICS OF
THREE NIGHT VISION DEVICES (NVD)

	NVG (2d Gen.) AN/PVS-5	NVG (3d Gen.) AN-AVS-6	PNVS/IHADSS
Sensor: Spectral sensitivity range	0.4 - 0.9 microns	0.55 - 0.95 microns	0.75 - 1.2 microns
Mass NVD adds to flight helmet	0.91 kg	0.75 kg (front) 0.17 kg (rear)	0.55 kg
Mass of helmet and NVD	2.3 kg	2.1 kg	1.86 kg
Visual acuity to normal eye	20/50*	20/40	20/40
Image field-of-view	40° x 40°	40° x 40°	40° horiz. 30° vert.
Range of focus	25 cm to infinity	25 cm to infinity	N/A
Dioptric control	-6.0 D to +2.0 D	-6.0 D to +2.0 D	-3.5 D to +3.5 D
Spectral characteristics of phosphor image	0.560 microns	0.560 microns	0.543 microns
Intensity of phosphor image	~ 2-3 fL	~ 2-4 fL	0.3 to 1.50 fL

* Sees at 50 feet (15 meters) what normal eye sees at 20 feet (6 meters).

AEROMEDICAL RESEARCH WITH NIGHT VISION DEVICES

The U.S. Army Aeromedical Research Laboratory (USAARL) has been actively involved in the development of these systems, including technical issues such as display design specifications, phosphor research, and cockpit lighting compatibilities. This research review focuses mainly upon aeromedical lessons learned relative to aviator performance and adaptation with these systems.

Second-Generation NVG

Some of the areas of investigation with AN/PVS-5 NVGs at USAARL and a brief description of the results:

(a) One of the early tasks in dealing with NVGs was to determine if all Army aviators would be able to use them. Visual acuity was measured through the NVG, and astigmatism of 1.00 diopter (or more) was found to reduce VA from 20/50 to 20/60 or worse. This represented a problem, since approximately 4 percent of the Army aviation population has 1.00 diopter or more of astigmatism. Flight surgeons in the field were advised to screen all aviators' medical records, update refractive exams in marginal cases, and check their VA through the goggles. Those pilots achieving VA of less than 20/50 with the NVG were not allowed to fly NVG missions. Spherical myopic and hyperopic corrections generally were not a problem, since the NVG could be adjusted for -6 diopters to +2 diopters.

(b) Contrast sensitivity was measured in the laboratory with the NVG and unaided eye at four average luminance levels using electronically generated spatial gratings (Wiley, 1976a). The luminance levels used corresponded to those of grass under a 5 percent, 25 percent, and full moon illuminance with no overcast and at 25 footlamberts for comparison purposes. At the equivalent of 100 percent moon illumination, the unaided eye achieved better contrast sensitivity at high spatial frequencies (> 8 cycles/degree); and with the NVG achieved better sensitivity in the low and medium spatial frequencies, which frequently relates to seeing a tank, wires, etc. (1-8 cycles/degree). At 5 and 25 percent moon illumination, performance is better with the NVG than the unaided eye at all spatial frequencies (bar widths) (Figure 5).

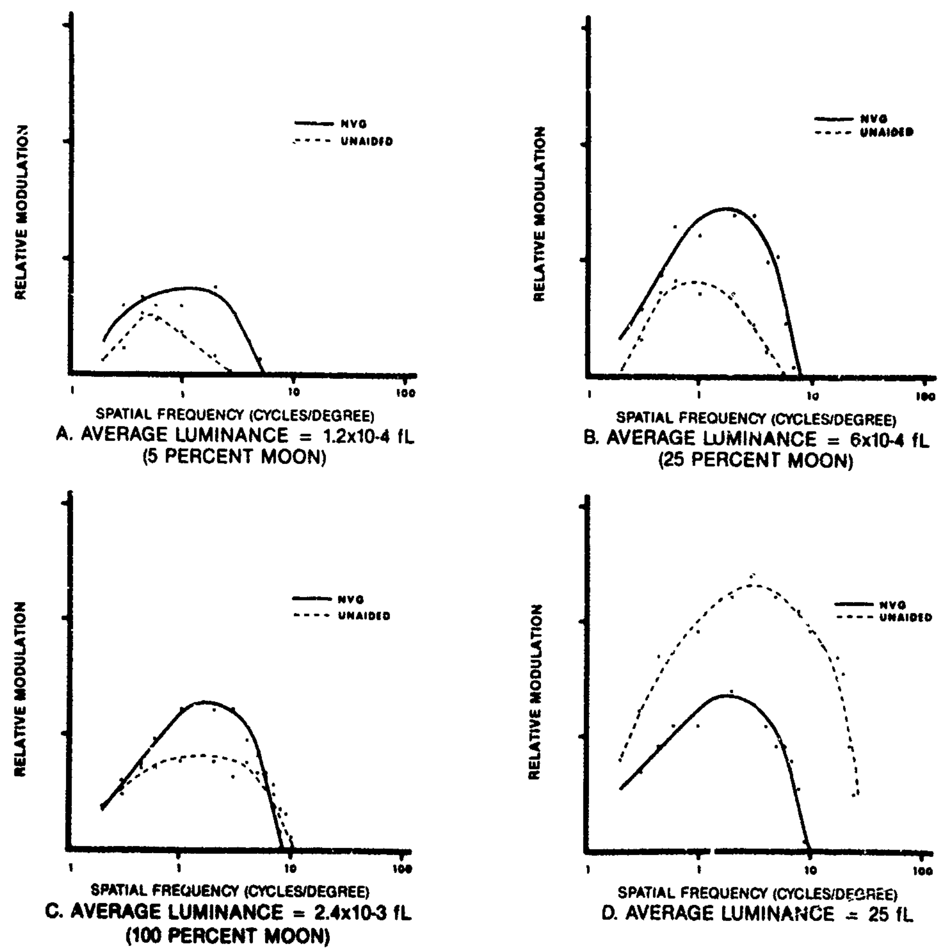

Figure 5. Comparison of NVG and unaided contrast sensitivity (modulation transfer functions).

(c) Depth perception was measured with and without the NVG in the laboratory at 20 feet and in the field from 200 to 2000 feet (Wiley, 1976b). A modified Howard-Dolman apparatus was used in the lab, measuring primarily stereopsis. At 20 feet the linear target separation threshold, expressed as standard deviation of linear displacement scores, was increased approximately 3.5 times with NVGs under full moon (.012 footlambert) illumination compared with unaided binocular vision under photopic conditions. Binocular NVG performance was slightly better than monocular photopic viewing (Figure 6).

The field study primarily examined monocular cues since the distances used were mostly beyond the range within which stereopsis is very effective. The subjects sat inside the cockpit of a parked UH-1H aircraft and looked at targets placed in pairs at various distances. Targets were moved in relationship one to the other and the subject's task was to indicate when the two targets were at the same distance. In general, the best performance was with monocular observation in the daytime followed closely by that with binocular observation in daytime; and the poorest performance was with unaided vision at night. The performance with the NVG was roughly midway between unaided daytime performance and unaided nighttime performance (Figure 7). The separation threshold was increased approximately 1.6 times with NVGs under full moon illumination when compared to unaided day vision.

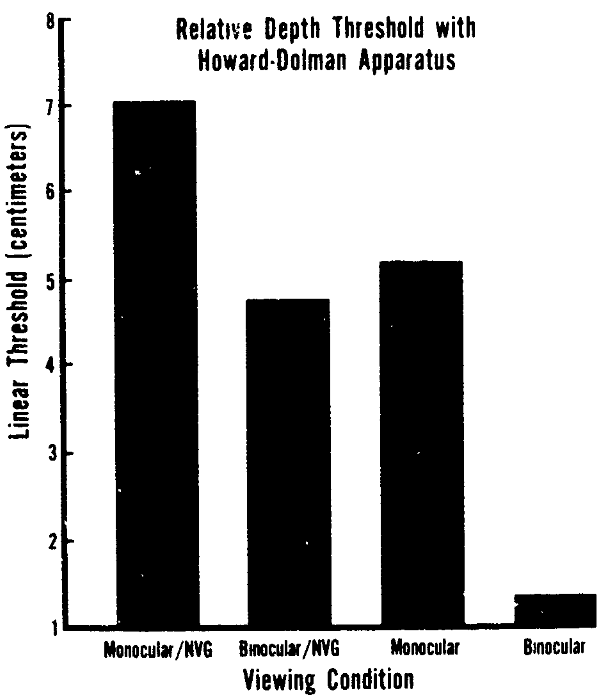

Figure 6. Relative depth threshold with Howard-Dolman apparatus at 20 feet under two viewing conditions (NVG at 0.12 foot-lamberts and unaided vision at 6.4 foot-lamberts).

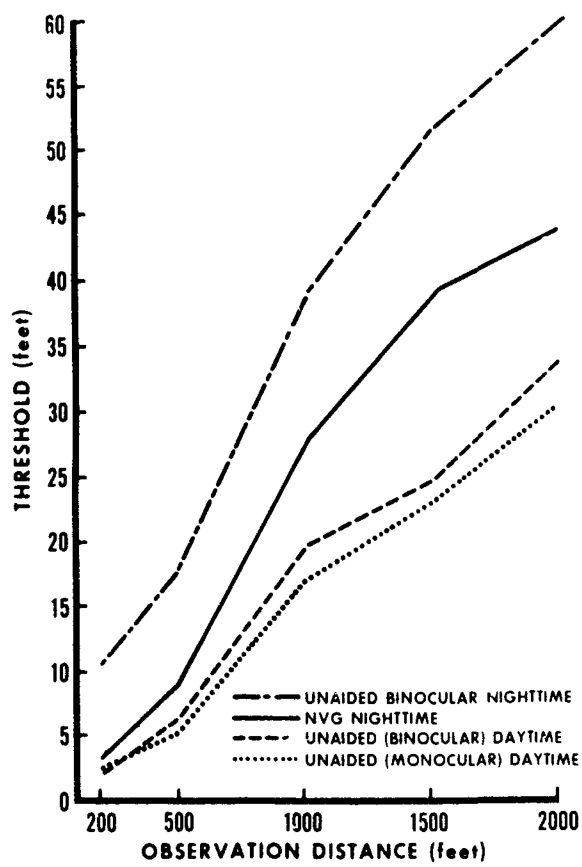

Figure 7. Linear thresholds for relative distance discrimination under four viewing conditions.

(d) The reduction of dark adaptation with the use of NVGs was measured, and the recovery time determined for readaptation, should the goggles be removed during flight (Glick, 1975). Dark adaptation curves were developed on six male subjects, who were initially preadapted at 662 footlamberts for 2 minutes. Dark adaptation then was measured for 30 minutes, followed by wearing the NVG for 5 minutes and measuring adaptation levels until the 30-minute level was regained. The average loss of dark adaptation using the NVG was from the 30-minute sensitivity level to the 10-minute level. The average time required for full recovery was 2 minutes (range 1.5-3), half of that occurring within 30 seconds (Figure 8).

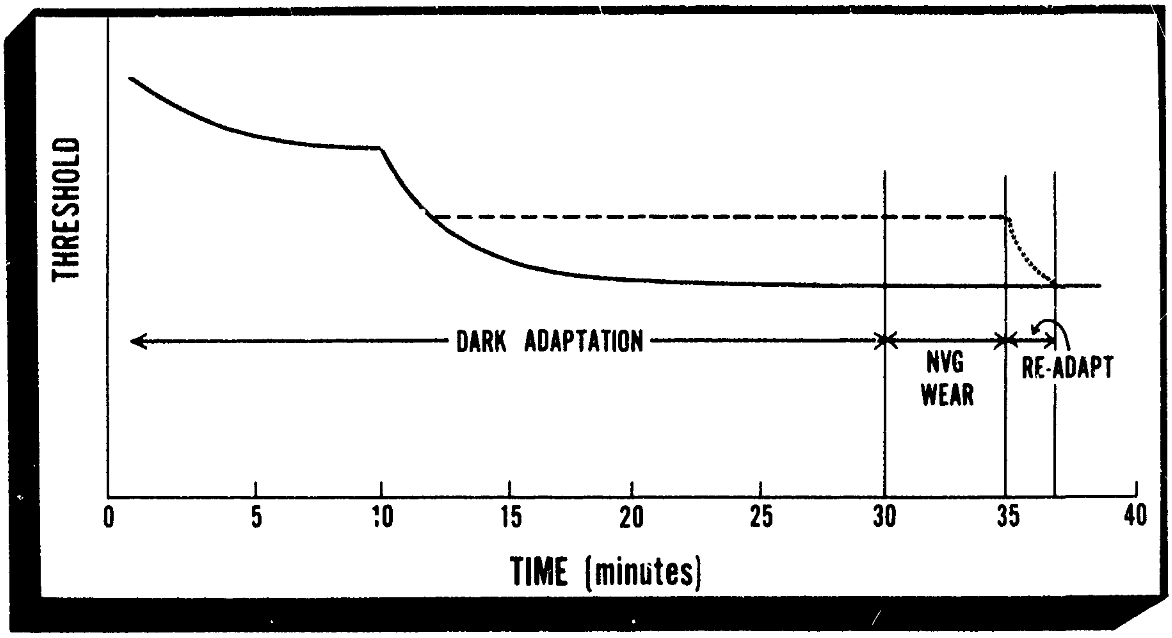

Figure 8. Typical curve showing dark adaptation, NVG wearing time, and dark adaptation recovery after goggles are removed.

(e) Day training filter concepts and specifications were developed and evaluated at USAARL in response to safety and logistical requirements related to initial NVG training for student pilots (Behar, 1977). The advantage for the instructor pilot having full daylight vision while the student pilot is undergoing initial familiarization with the NVG is quite apparent, as is the logistical advantage of not having to depend so greatly on the moon and the weather.

(f) After a midair collision in the traffic pattern with NVGs at Fort Rucker in 1981, it was apparent that the limited field-of-view and blocking of peripheral vision by the faceplate of the AN/PVS-5 was an unacceptable safety hazard in high density flight areas. USAARL designed, developed, and evaluated a modified faceplate for the NVG which now has been implemented by all three military services (McLean, 1982). This modification, shown in Figure 1, allows underneath unaided view of the instrument panel, some lateral peripheral vision, and the wearing of spectacles.

(g) Now that corrective lenses can be worn with the modified AN/PVS-5 (and ANVIS), there is concern about the relative safety of different spectacle lens materials. Therefore, polycarbonate, plastic, and standard tempered glass lenses have been evaluated for fracture resistance when impacted with the eyepieces of NVGs. A head form drop device and simulated NVG were used in testing. Glass and plastic CR39 lens pairs shattered at drop heights of 6 and 18 inches, respectively. No failures of polycarbonate lenses were recorded with drops from up to 6 feet. During the next 6 months, USAARL is sending polycarbonate spectacles to those Army aviators who require spectacles with NVGs. In the process, data will be collected on durability of the lenses in the field.

(h) As aviators became NVG qualified in larger numbers, there were increasing complaints of neck fatigue in the posterior cervical muscles during NVG flight. The fatigue resulted from the forward shift of the center of gravity of the flight helmet with the goggles attached. This problem was aggravated further by the modification of the faceplate, since the weight of the goggles no longer rested against the face and the mounting point was moved forward to the anterior edge of the flight helmet. The best quick-fix appeared to be the mounting of a counterbalancing weight at the rear of the helmet. This was accomplished with a small canvas bag, attachable with Velcro, in which each aviator could place the desired amount of lead weights. Evaluation of this device revealed a fivefold reduction in helmet adjustments by aviators during flight, reduced fatigue, and increased mission time.

(i) In an extended flight NVG workload study, 10 NVG instructor pilots flew two 6-hour missions, one mission with the unmodified AN/PVS-5 using daylight filters, and the other with unaided vision during daylight (Stone, 1984). A crossover matrix was used, the mission days being separated by one day of rest. Two of the pilots did not complete the NVG mission. One was withdrawn at 3.5 hours with tremors of the extremities, and the other withdrew at 5 hours from extreme discomfort. Flight performance was not significantly altered during the extended NVG flight for the remaining eight aviators. Postflight questionnaire responses revealed a concern with lack of concentration and a decline of mental alertness with extended

wear of NVGs. These aviators recommended 4 hours/night maximum NVG time, 12 hours/72 hours, and 20 hours/week. Even though this group had low NVG flying time (mean 39 hours), similar subjective recommendations have shown up in other studies.

(j) Inspiratory minute volume (IMV) data was obtained from a series of flights with subjects flying OH-58, UH-1H, and AH-1G helicopters (Pettyjohn, 1977). IMV determinations were obtained by Mueller respirometers connected to the aircrewman's oxygen mask. Five phases of flight were evaluated--runup, take off, cruise, threat, and final approach. The helicopter flight profile was evaluated under routine nap-of-the-earth (NOE), night nap-of-the-earth (NNOE), and night vision devices (NVD). The minimum period for any IMV sample was 10 minutes. The most useful information came from the UH-1 data, which included IMVs from all four flight scenarios (routine, NOE, NNOE, and NVD). The OH-58 was flown only under the routine scenario and the AH-1 only under NOE conditions during daylight. During the threat phase of NOE and NNOE flight in the UH-1H, IMV increased twofold; NVD flight was associated with a threefold increase through most phases of the scenario (Figure 9). These data must be interpreted cautiously for the following reasons: The work was done when aviators had little training or experience with NVG flying; many myths were associated with their use; and wearing both the unmodified AN/PVS-5 and an oxygen mask simultaneously must have been cumbersome, probably resulting in serious visual problems. Nevertheless, this work gives some insight into combined crew stress/workload with NVGs. It is reviewed here because it is provocative and bears repeating under more controlled conditions, to include oxygen uptake studies as well as IMV.

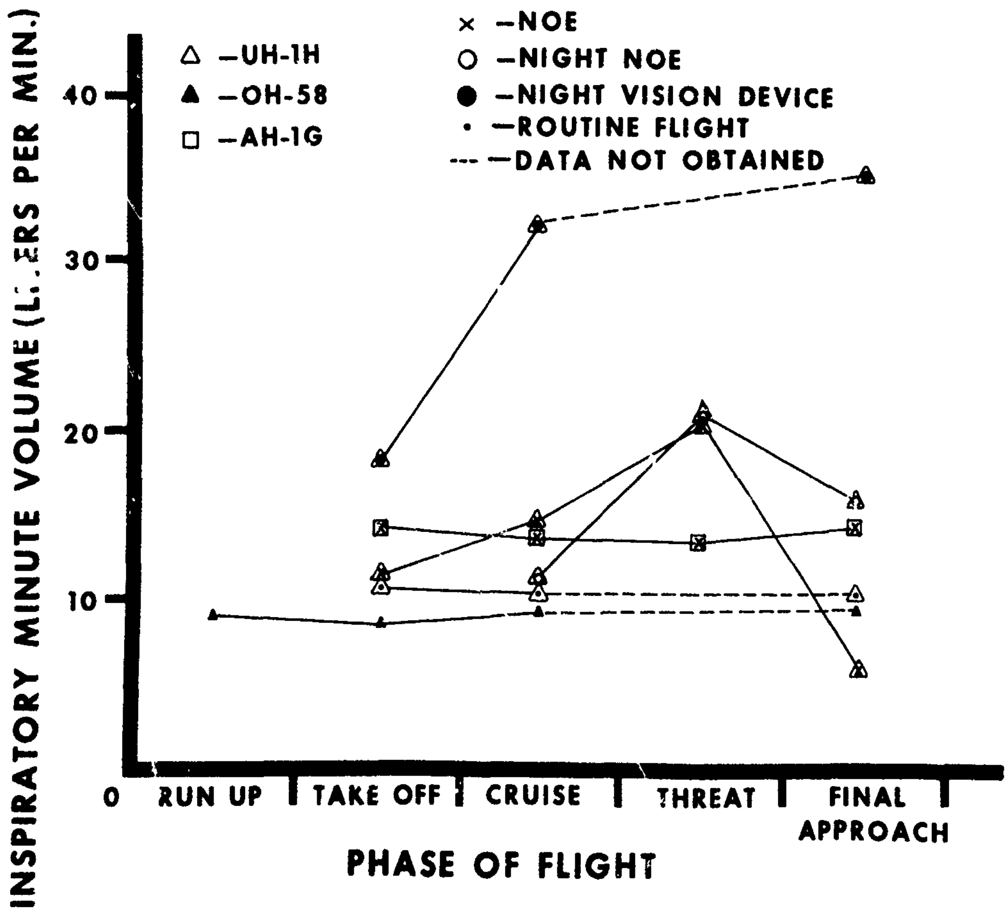

Figure 9. Comparison of mean inspiratory minute volume measurements for aviators piloting UH-1H aircraft under 4 different scenarios (and AH-1G and OH-58 each under one scenario).

Third-Generation NVG (ANVIS)

Although USAARL has not repeated the AN/PVS-5 research efforts with the third-generation ANVIS, certain assumptions can be made and much of the work can be applied. It is true that performance with these goggles will be improved significantly; the big difference with the ANVIS is that they will allow flight operations at lower night illumination levels.

Visual resolution of the resultant image will be improved slightly, with achievable VA of 20/40 compared with 20/50. Because of the inherent design for aviation, corrective lenses can be worn; and viewing of the instrument panel, map reading, and lateral peripheral vision are improved.

Contrast sensitivity will be modified because of the marked improvement in performance sensitivity of the ANVIS. The human response at 25 percent moon with the AN/PVS-5 would now closely resemble the response under starlight with the ANVIS (Figure 5). Pilot performance in hazard detection with the ANVIS is shown compared with AN/PVS-5 in Figure 10, which demonstrates findings during operational testing by the Army Aviation Test Board (Neal, 1983).

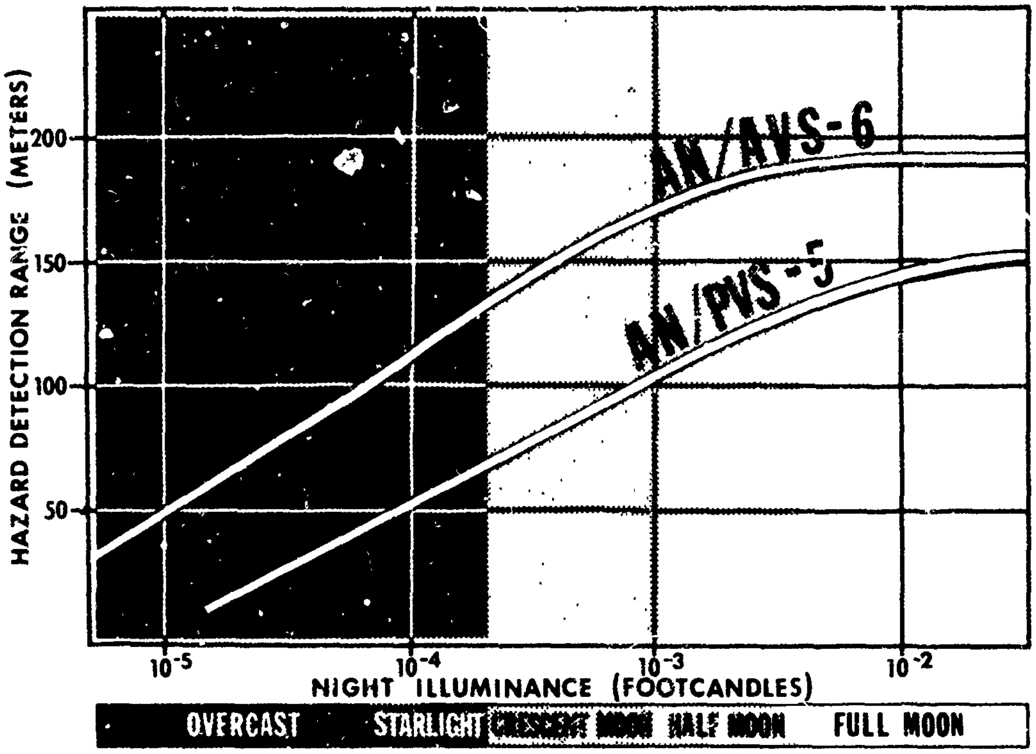

Figure 10. Hazard detection ranges by pilots with AN/PVS-5 and ANVIS (target used was a pole 15 centimeters in diameter and 3 meters high).

Depth discrimination limitations should be changed very little.

Recovery of dark adaptation will be virtually unchanged because the light intensity of the phosphor image presented to the eyes will be in the same general range.

ANVIS retains the potential for daylight training with various filters to simulate differing night light levels. Eye cups are required, and have been designed, to allow trainees to look under at instruments.

Neck fatigue will be reduced with the ANVIS because of its lighter weight and because of the rear helmet mounting of the dual battery pack. Little or no additional counterweighting will be required.

Workload will be reduced slightly with ANVIS compared with operation with AN/PVS-5 under the same lighting conditions. However, aviators will simply fly more nights, and mission capability will be extended; as a result, overall crew stress/workload will be altered very little, as will crew rest guidelines.

AH-64 PNVS and IHADSS

Aeromedical research with the monocular AH-64 night vision system is limited. A relatively small number of instructor pilots have been trained to date.

Those aviators with as much as 1.00 diopter of astigmatism generally do not obtain adequate resolution with this system. Although the IHADSS allows for correction of spherical myopic and hyperopic refractive error, correction usually is required for both eyes; therefore, spectacles (or contact lenses) will be necessary. To manage this problem, modified spectacles were developed so that the helmet display unit would not be held out of position by the inferior-lateral portion of the right lens. This has been accomplished by cutting away that portion of the lens and modifying the spectacle frames. A determination then was made regarding adequacy of field-of-view using this modification of the spectacles with the IHADSS. This was accomplished using an IHADSS with a computer-generated display and testing a number of pilots with and without spectacles. At present, constriction of field-of-view appears not to be a problem. However, as larger numbers of aviators are trained, some may

be found with prominent cheek bones and deep set eyes who cannot get the combiner lens properly aligned within the 10 millimeters eye relief allowed by the system.

An attempt was made to establish some correlation between eye dominance and number of flight hours required for transition training in the first 16 pilots trained with the IHADSS. Since the helmet-mounted display was on the right side, some investigators felt that the system would be more compatible with strong right eye dominance. This did not turn out to be the case. Using a variety of measurements for eye dominance, including the stereocampimeter, there was no correlation between measured dominance of either eye and time to completion, which ranged from 16.1 to 25.3 hours. There was only a faint suggestion that those aviators with relatively low eye dominance for either eye may have shorter training times. Continued study of larger numbers should resolve this question. Incidentally, there was no significant change in eye dominance during training with the system.

Studies with the PNVS and IHADSS to determine aviators' loss of dark adaptation (and recovery times), and workload studies for comparison with NVG, have not yet been undertaken, but are clearly indicated.

CURRENT PROBLEM AREAS

Persistent problem areas with night vision devices receiving continued attention include the following: Excessive head supported weight; difficulty for some pilots in relaxing accommodation when adjusting focus; difficulty for some in alignment of optical center with pupillary axis; reduced field-of-view which increases head movement, thus crew workload and susceptibility to vertigo; inadequate contrast related to the monochromatic visual image; cockpit and position lighting compatibility; difficulty with map reading; lack of user's ability to adequately evaluate NVGs for defects (signal to noise, image quality, gain) prior to flight; integration with CBR masks; hardening against potential countermeasures; and inadequate estimation of available electromagnetic radiation and weather influences for each given area of flight operations.

Additional problems with the IHADSS include: Unanswered questions regarding eye dominance and retinal rivalry as determinants of successful use; unique problems of integration with chemical/biological and laser protection; and fit and alignment problems for those aviators with unique anatomical features.

CONCLUSIONS AND SUMMARY

As mission requirements and technology advance, the role of night vision devices in Army aviation will continue to expand. Despite technological improvements, operational problems remain. The challenge facing the military community is to resolve these problems through careful design, testing, and evaluation to include continued aeromedical research. And this is clearly an area which deserves particularly close attention by members of the operational aeromedical community. Their active participation in training and flight operations with night vision devices will increase flight safety and provide observations that will make easier the resolution of existing problems.

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DISCUSSION
Papers 5—8

5. Dr Breitmaier presented by Dr Reetz - USA - Visual and Spectroradiometric Performance Criteria for a Night Vision Goggles (NVG) Compatible Aircraft Interior Lighting Specification.
6. Lt Col Genco presented by Dr Susnik - USA - Night Vision Support Devices: Human Engineering Integration.
8. Col Price - USA - Aeromedical Lessons Learned with Night Vision Devices.

Langoff - GE: Col Price stated that the perception threshold of the unaided eye was monocularly better than two eyes. I cannot believe it. Has he any explanation for this physiological miracle? Also, is the miniature CRT compatible with glasses?

Price - US: I neglected to mention how we studied depth perception in the field, and what was done. We set up a number of rectangular bars varying in width and height so that the same angle was sub-tended at the eye at distances from 200 - 2000 ft. We had a tracker line up the bar that was deviated and we moved the two bars apart from each other and the subjects had to line them back. Basically it looked as if monocular cues in that environment over 200 ft are even more reliable than binocular cues and although the difference in the two was not statistically significant, the way they turned out is plotted on that curve. The monocular cues looked to be more important. Maybe Dr Brennan would have some ideas about that.

Brennan UK: Yes. I find it surprising, but of course, NVGs do degrade stereopsis significantly and I will be talking a little bit about this on Thursday. In essence the distance at which you are able to perceive stereopsis is dependant on the value you accept for the minimum detectable instantaneous parallax and this value will be degraded when wearing NVGs from the very small values perceivable with the naked eye of about 4 seconds of arc. I am not saying that stereopsis is not important with NVGs, just that it is less effective than with the naked eye. A question for Col Price, are your polycarbonate spectacle lenses hard coated?

Price US: Yes.

Brennan UK: Do you find that when you hard coat them that you degrade their impact resistance?

Price US: No, but we really have not studied that problem. What we did was to take a few pairs that were coated; regrettably our drop device only went to 6 ft so we could not test them any higher.

Brennan UK: When our polycarbonate visors are hard coated their performance is so degraded that we now no longer coat them. I would like to use anti-reflection coated visors, because reflections are a great problem, but if we anti-reflection coat we also degrade impact resistance. A question for Capt Susnik. Can you get enough light through a shared aperture small enough to give you the increased depth of field you require? Even if you can why don't you just make a slightly bigger hole and put a 1 or 1.5 dioptre lens in it?

Susnik US: The aperture should be big enough the way it is to get enough light because it is still going through the amplification system. You are not looking at the far field scene, you are ignoring the dot in your scene when you are looking at the far field, but when you are looking at your gauges you are looking for this little dot.

Brennan UK: The actual lenses will be focused on infinity because you are using the whole of the lenses when you are looking externally, so you are making a pinhole on a lens that is focused to infinity and you thereby achieve sufficient depth of field to focus close to.

Susnik US: Yes. You are never re-focussing the tubes, you just fixate the dot.

Brennan UK: Another way would be to remove a larger area of your red filter and fit a small positive lens of the appropriate power.

Susnik US: You may degrade your long vision.

Brennan UK: No, not if you use a small lens 1mm or so in diameter you will get enough light through and you will get a focus related to the power of the lens.

Lang: Is the miniature CRT compatible with the wearer of glasses?

Price US: Yes. On the integrated HDS the spectacles have to be modified as I indicated, we have to grind off the lower 25% of the lens inferiorly and laterally and then bend the frame. We were concerned that we would have to move the combined lens out too far from the eye and would get a loss of field of view and some of the imagery around the periphery, but this was not the case. We looked at a number of pilots with the modified spectacles and they had no loss of field of view. Now, there are some other problems that may occur as we purchase the larger size of helmet to accommodate the chemical protective mask. It introduces some new optical problems, it is a stocking like arrangement which comes over the face and has lenses behind the combiner plate. We cannot afford to give every pilot two helmets so they will have to wear a space occupying stocking when they are not wearing a chemical mask. That interposes a problem which is being dealt with. The simple answer to your question is, yes, you can wear spectacles with it.

Draeger GE: May I add one little remark to what Dr Brennan has explained about binocularity. Looking through NVG means looking at a two dimensional stream so this explains the small difference between the binocular and the monocular discrimination of depth.

Brennan UK: Yes, that is true because the disparate information is so degraded. Stereopsis relies upon the different appearance as seen by the two eyes and it is accurate when acuity is high. When acuity is low it is degraded, I agree.

Santucci FR: You have established your technical specification for goggles by mainly using physical rules. Have you established any correlation with psychophysical measures? Apparently during the day you use colour coding of information and at night coding by luminance variation. Do you believe that pilots can easily adapt from day to night? Can they adjust quickly to the two types of coding systems?

Reetz US: To answer the first question, the psychophysical implications of this particulr colour we have selected are being studied right now at U.S. Air Force Aerospace Medical Research Laboratory (AMRL) by Mary Cerry. So the basic answer to your question is that we do not have all that much data at the present time although we will attempt to collect it in the future. With regard to your second question with the colour coding we are implying that this particular lighting system would be the only lighting system in the aircraft. In other words we are converting from a three colour lighting system to a dual colour lighting system for use all the time, we are not implying that we are going to have different display configurations night and day. The reason we did that is that we feel that the master caution light needs to gain your attention so it will be a different colour than the rest of the cockpit lighting. Once the master caution light attacts your attention you would look to your enunciator panel to see what the caution event was.

Bohm GE: You mention also using a yellow colour with your NVG, for the cockpit lighting. Is it only for the 3rd generation tubes and are you then using filters in front of the 3rd generation tubes because sensitivity of the tubes is high at about 550 to 570nm.

Reetz US. We are only talking about the third generation image tubes. The yellow that we are achieving, as you will notice with the ANVIS radiance, was a factor of about 100 higher than the rest of the instrument panel. We have done some tests with lights of this design and we have indeed found that they are bright enough to see and they do not degrade the amplification characteristics of the goggles. You really cannot get it much dimmer in terms of the ANVIS radiance and still maintain this yellow. It has been achieved by a particular manufacturer through use of LEDs, it is very difficult to achieve that with an incandescent display and still maintain daylight readability.

Spinoni IT: For the NVGs you showed with superimposed symbology. How is this symbology correlated to the external world. If you move the head what happens to symbology?

Susnik US: The symbology is tied right to the goggle itself so if you turn your head the symbology stays in your field of view. You can look at different areas but you will still see the symbology in the same position.

Spinoni IT: When you are looking to the front, if you move your head is it still correlated directly in front of you. If you move the head from left to right is the symbology changing?

Susnik US: It is moving with the head movement, it is physically mounted to the outside of the NVG, so as you turn your head it moves as well.

NIGHT VISION BY NVG WITH FLIR

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SUMMARY

Night Vision Goggles and fixed forward looking Infra-red equipments both have particular operational shortcomings when used in a fixed wing aircraft for close air support at night. However when operated together, they compensate for each others' deficiencies forming a highly capable system at far less cost and complexity compared with other night vision systems.

1. INTRODUCTION

The ability to operate effectively at night has long been a goal of every airforce in the world, for two very good reasons: one, without an air threat the ground based enemy can redeploy at night more easily; and two, that night period occupies a large slice of time - around 40 percent of the European winter's day, as shown in Figure 1. This shows the time when you could fly visually if only you could see in the dark.

It's not surprising, therefore, that night vision equipment for flying has been with us for many years and has been the object of much time and resources in development.

GEC Avionics have been active in the development of night vision sensors and display systems for both rotary and fixed wing aircraft. This paper describes some of our flight test experiences in the fixed wing field.

2. EARLY FLIR TESTS

In 1970, we supplied equipment for a simultaneous trial of both low light TV and Forward Looking Infra-red (FLIR) on a Vought A-7 aircraft, with the sensors mounted in pods. After much comparison of the relative merits and problems of Low Light TV and FLIR, the infra-red side eventually won the day. The reason was that it could produce a better picture for more of the time than the Low Light TV, and it was also immune to washout by bright lights. However FLIR did not have the monopoly of providing a good picture, and for a while the A-7 programme was scheduled to follow a multisensor approach, with both FLIR and LLTV. Fifteen years later we find that history is repeating itself as so often happens, and those advantages uncovered in the multisensor approach are turning up again - but with some different hardware.

The A-7 sensors were switched so that either could be shown on the Head Up Display, to enable direct comparison of the two. The Head Up Display, shown in Figure 2, had a fairly small field of view by today's standards. The instantaneous view, without moving the head was just over 12 degrees, with a total field of view of 20 degrees. In spite of this small field of view, the fact that the display was collimated gave you the impression of looking through a port hole on the outside world. Add the normal Head Up Display symbology to the picture, and you have effectively duplicated the daytime conditions - as long as you only look at the display and not through the canopy sides. Even so, the pilots found they were quite able to fly and manoeuvre the aircraft at low level, and to pick up targets - as long as they were flying towards them.

3. OTHER SOLUTIONS

Later programmes tried to overcome this lack of ability to look off-track, by adding gimbals to the FLIR. However this gave a new set of problems: how do you represent a picture that is not looking where you're going on a display that is firmly fixed in front of you? In addition, you now have to control the FLIR direction by a hand controller or similar, set the magnification, and interpret what it is you're actually seeing. Add to this some lag or overshoot on the gimbals and the illusion that you're seeing the real world is lost. Your work load goes up to a level where you are uncomfortable flying at low altitudes. So you pull up to fly higher. Because any sensor picture is poorer as you fly higher you are now more uncomfortable, so you go even higher and so on, becoming more and more vulnerable to enemy detection.

Some gimballed systems of course have become successfully refined for particular tasks, such as the A-7 FLIR and USAF LANTIRN programmes, but for low level close air support the overriding need is for a system that is easy to fly. This implies other advantages such as minimal retraining and fast acclimatisation of a daytime pilot. In short, the overall goal should be to project the normal daytime VFR procedures into the hours of darkness. Only then will the pilot feel comfortable to fly at the low altitudes where he is most effective.

4. FLYING WITH NVG

Around the time when this debate of gimballed sensors and methods of display was going on, one of the test pilots at RAE Farnborough tried the unthinkable. Sqn Ldr Jerry Fisher took a set of night vision goggles that had only been used on the ground or in helicopters, and flew with them in a fixed wing Hunter aircraft. He wrote a report that started some rethinking in the night vision world, and resulted in a new way of flying fixed wing. At a stroke, NVGs provided the essential elements missing from a simple fixed FLIR:

- Excellent look-around capability
- Good field of view
- Failure - survival redundancy

You could now look around with completely natural head movements, giving you excellent orientation from what was happening all around you. Your head movement told you where you were looking, so no need for difficult-to-interpret line of sight indicators. You could pick out a target away from the aircraft track. You could see into turns, vastly improving your manoeuvreability. The field of view was better than any available Head Up Display and when you're flying low level and fast, it was a comfort to know that you have a backup way of seeing where you're going in case the FLIR or display fails.

5. RELATIVE SHORTCOMINGS

However, NVGs are still, even today, no substitute for a good FLIR, for several reasons.

- No true infra-red capability
- Limited sensitivity
- Limited resolution
- Limited dynamic range
- Scene is viewed through canopy

The so-called near-IR band in which all NVGs operate still requires illumination from the sky and so is affected by cloud cover and the state of the moon. On the other hand thermal differences are always present, especially highlighting interesting targets like vehicles and troops. True IR is relatively unaffected by haze or smoke, whereas NVG effectively operate under existing visibility.

NVGs are designed down to a minimum weight, so their image performance is somewhat limited. Low dynamic range tends to lose detail in some low or high highlight areas. With FLIR being aircraft mounted, more space exists for comprehensive facilities in picture control and enhancement. NVGs have to view the scene through the canopy and this can attenuate the NVG spectrum and limit their ability in the low light levels. This will be further degraded if the cockpit lighting has not been totally corrected, and reflections off the canopy confuse the outside image or artificially reduce the gain of the NVG. Thus the NVG and FLIR do complement each other both in performance and method of use, providing real advantages when combined.

6. VIEWING HUD BY NVG

However a difficulty exists when you are wearing conventional NVG; you can only see your FLIR picture on the HUD by viewing it through the NVG. Their limited performance compared with the FLIR and HUD will reduce the resolution and dynamic range of the FLIR picture. To overcome this difficulty, we invented a new NVG that combines the intensifier image optically with the direct view of the HUD.

7. CATS EYES

Compared with the straight through goggles, where the eye looks into or around the eyepiece, the new NVG has a combining eyepiece as shown in Figure 3 that allows a direct view even when the NVG is turned off. Called Cats Eyes, the NVG shown in Figure 4 provides you with a much clearer view of all cockpit instruments and controls as well as the HUD. The HUD image is prevented from entering the intensifiers by the normal complementary filter used to reject cockpit lighting. Since the FLIR picture is now seen only by direct vision, it suffers no reduction in resolution or dynamic range.

8. FLIGHT TRIALS

Flight trials of FLIR and NVG have been conducted by RAE Farnborough on the 'Nightbird' Hunter programme, and by the United States Marine Corps on their 'Cheap Night' A-7 programme. The essence of the latter tongue-in-cheek title was to draw attention to the fact that a fixed FLIR plus NVG would turn out cheaper than a more complex gimballed system. Later this year General Dynamics plans to do similar trials in an F-16.

The objective of the trials was to demonstrate a night vision system for fixed wing aircraft that was easy to use, required minimal retraining of a daylight-trained pilot, could be used in all phases of a mission and was cheap. A pod mounted FLIR, shown in Figure 5, with field-of-view 20 x 13 degrees was displayed head up, boresighted and overlaid 1 to 1 on the real world. HUD symbology was added to the overall picture.

9. RESULTS

The results were most rewarding. Usually in night flying, looking around without NVG brings on rapid disorientation. With NVG however, the pilots' scan patterns made much use of look around and down to provide better orientation and appreciation of terrain. Even when light conditions were so poor that NVG would not pick up useful ground detail, the test pilots reported that they picked up the glow of the night sky on the horizon. This assisted orientation so much that it was worth keeping the NVG on the head.

When the pilots looked forward, their view was enhanced by the FLIR displayed on the HUD. Since this was collimated and boresighted to the real world, the FLIR simply appeared as an area of scene with better clarity.

The pilot's scan pattern depended on prevailing light and visual conditions, resulting in the better image coming from NVG or FLIR. The pattern ran through NVG - HUD - Head Down Display - Projected Map Display - Attitude Indicator, repeated approximately every 5-10 seconds. With conditions favouring NVG operation, these contributed 70 percent of the information, with FLIR 20 percent and other inputs 10 percent. Under poor NVG conditions FLIR gave 70 percent and NVG 10 percent, with projected map and conventional instruments providing 20 percent.

Other benefits were noted. The differing spectral sensitivities of the NVG and FLIR resulted in some objects being picked up sooner than with only one sensor. For example, some lights having a low IR emission were first noticed on NVG long before producing an image on FLIR. Some FLIR scenes can be misleading, such as smooth water that reflects the temperature of the sky or a river bank, rather than its own temperature. The NVG provided the second opinion that cleared the confusion.

The system could also be adapted by the pilot to suit prevailing light levels and flight conditions. With good ambient lighting where NVGs gave adequate performance for en-route navigation, the FLIR could be switched to a head down display, leaving symbology on the HUD. This provided as near a duplication of daytime conditions as possible, with the FLIR available head down for confirmation of the scene as required.

This facility of providing a choice for display surfaces was judged to increase the acceptability of the system and hence the operational effectiveness, since it was felt by the pilots that they had greater control over their procedures.

10 FUTURE DEVELOPMENTS

Looking ahead to how the system might develop, besides general improvement in FLIR and NVG image quality, the most significant item that would affect the way the system is used is probably the display. Although NVG provide the lookaround, a larger FLIR coverage would improve performance in marginal lighting conditions, especially in turning flight. A conventional HUD has a 15 degree vertical field of view, and the FLIR centreline is slanted down to present as much of the ground as possible. This is shown in the small rectangle of Figure 6. However in turning flight, this provides only 3 degree look into the turn. Going to a diffractive HUD such as LANTIRN effectively doubles this as shown. Even so, the display covers only a small part of the pilots total field of view. To increase this still further, a helmet mounted displayed is required, but now we are getting back to gimbals and more complexity.

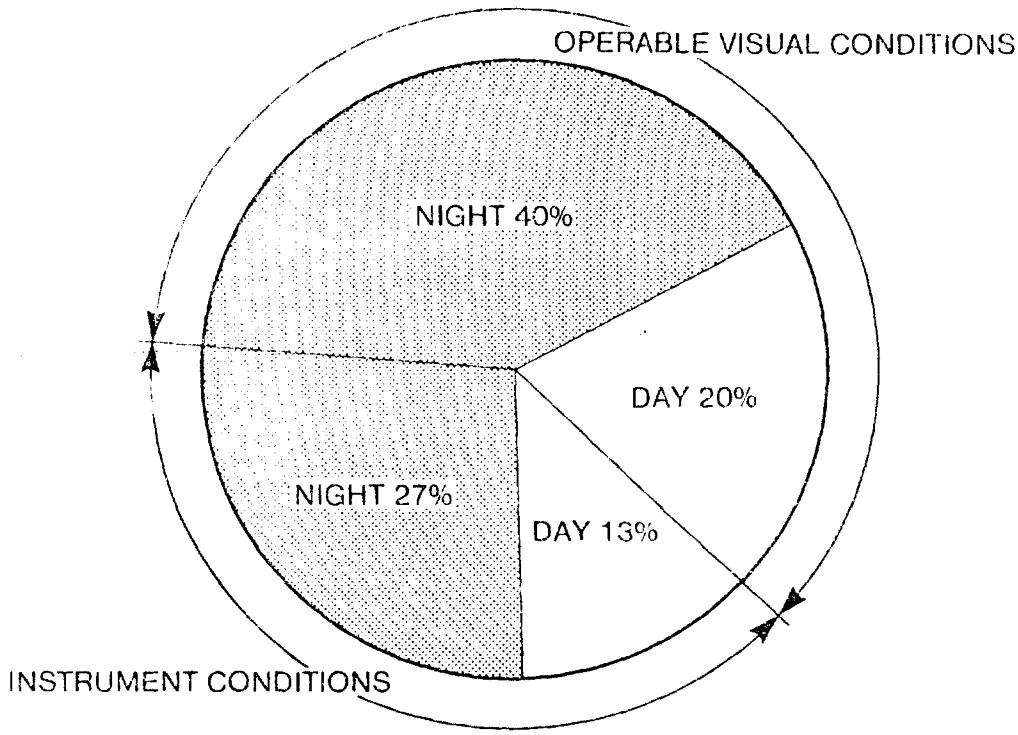
One limitation of the fixed 1:1 FLIR is that target recognition at long ranges is difficult without some optical magnification. An area for development being considered here is to equip the FLIR with a magnifying telescope that could be switched in only for the 40 milliseconds that it takes to store the resultant TV picture. A special HUD symbol would mark the centre of magnified field of view, and on command the picture would be grabbed to be frozen and displayed magnified on a head down display - shown in Figure 7 as close to the normal sight line as possible. Only a minimal interruption of the normal FLIR picture has occurred, and the pilot is able to identify his target as required.

11. CONCLUSION

To summarise the essential features:-

- NVG and fixed FLIR complement each other well
- The aim should be to duplicate normal daytime VFR procedures
- FLIR should be displayed head up with unity magnification and normal HUD symbols
- Display flexibility should allow pilot choice to adapt the system to prevailing conditions

The Need for Night Capability



WEATHER – CENTRAL EUROPE IN WINTER

FIGURE 1

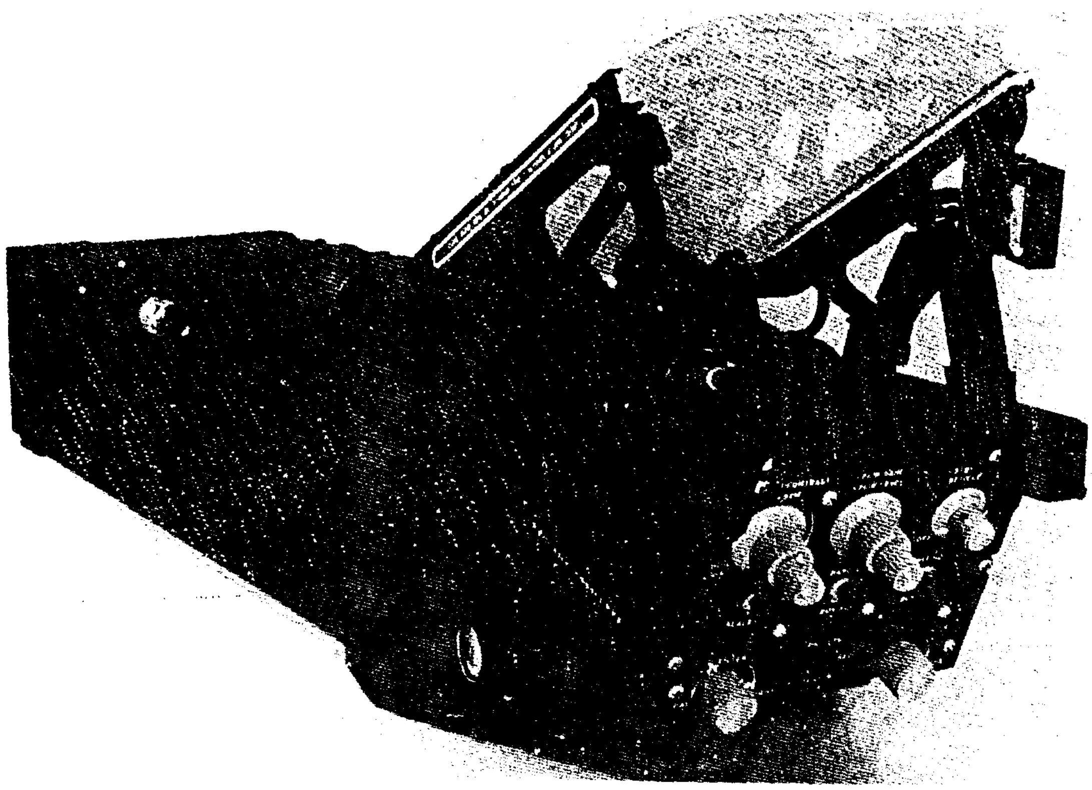


FIGURE 2 A-7 RASTER/CURSIVE HEAD UP DISPLAY

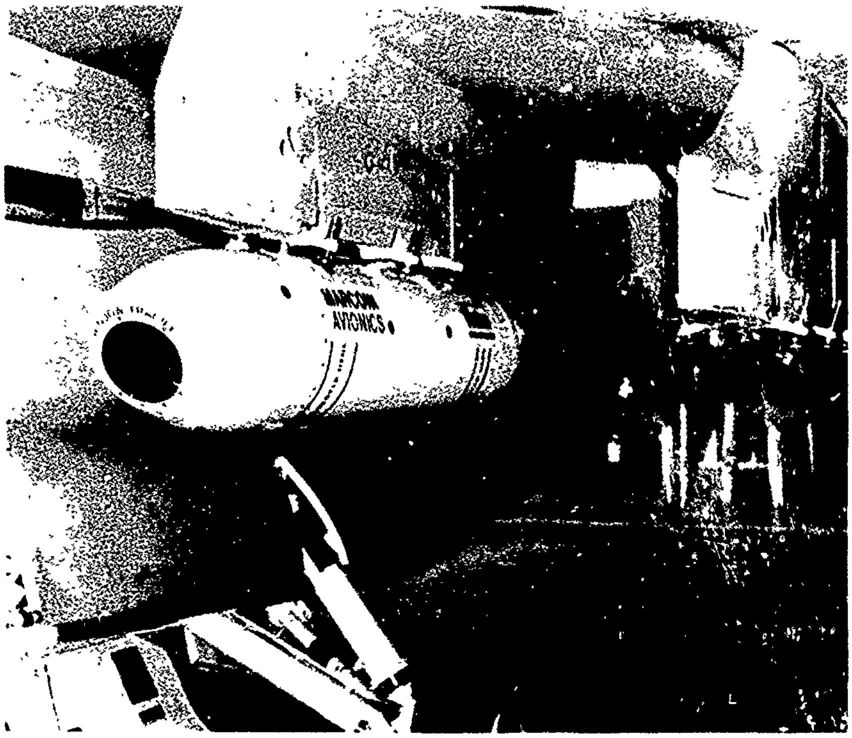


FIGURE 3 A-7 CHEAP NIGHT TRIALS FLIR POD

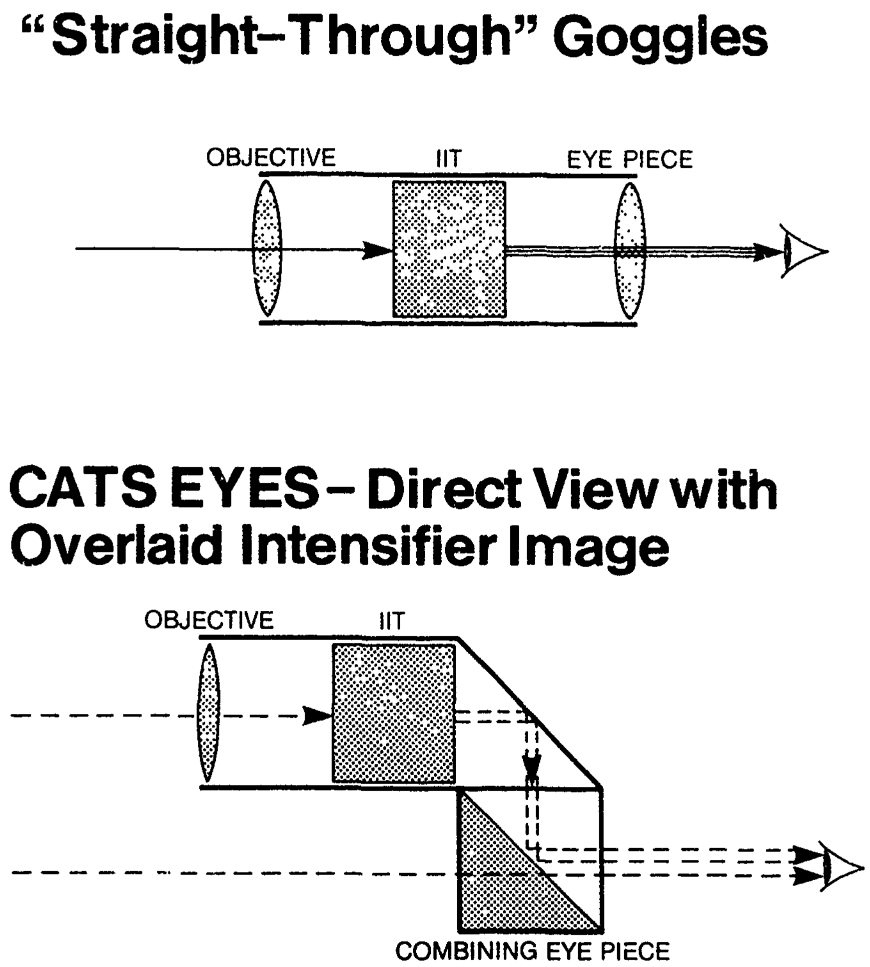
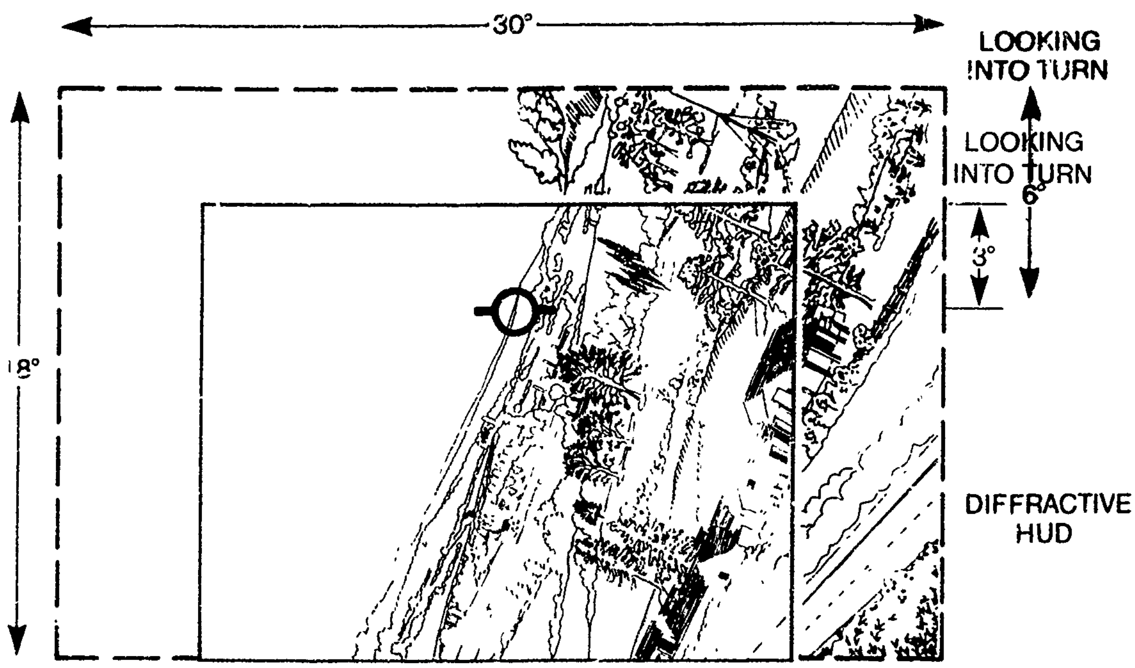


FIGURE 4

FIGURE 5 THE NEW CATS EYES NVG

HUD Field of View – Turning Flight



Diffractive HUD – 30° x 18° FOV Pilots Eye View

FIGURE 6

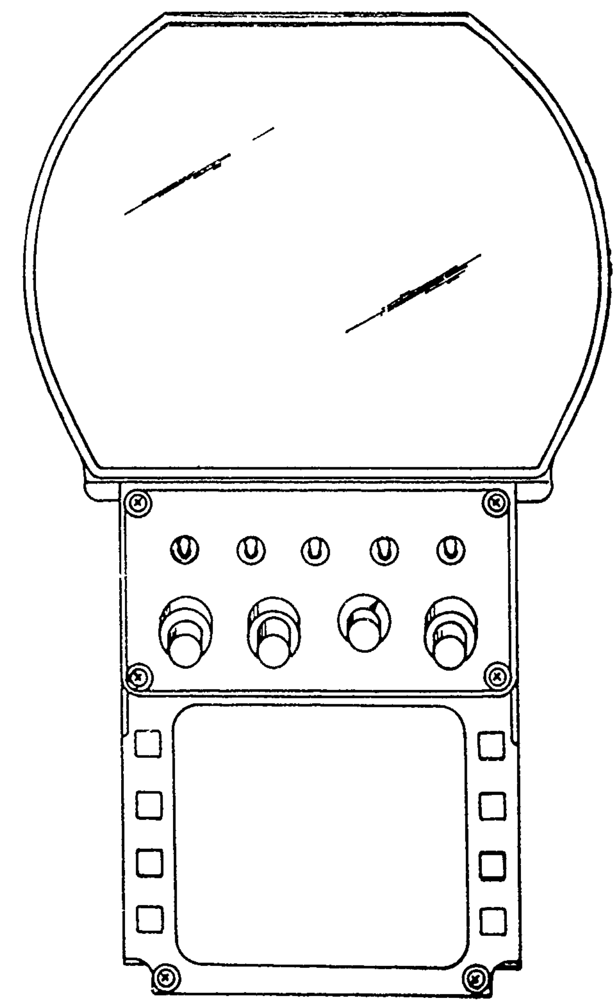


FIGURE 7 HEAD UP WITH EYES DOWN DISPLAY

PARTICULAR PROBLEMS OF AIRWORTHINESS FROM AN OPHTHALMOLOGICAL VIEW

by

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Navigation of aircrafts depends on visual acuity and optical perception in the main. Therefore ophthalmological evaluation is of major importance in aviation medicine. Each country uses own national medical standards for the three different pilot classes. But there still remain applicants not exactly meeting these standards (1 – 4).

In Germany, the "Fliegerärztliche Gutachterausschuß", a special expert board, is competent for these borderline cases in civil aviation. Some examples are given from the practice of this board showing the particular problems of appropriate decisions. Also the major differences of national regulations between Germany and the USA will be discussed, comparing civil and Air-force standards.

To start with, the national standard for visual acuity are quite diverse, mainly for the visual acuity without correction (fig. 1).

For illustration, let's take the cases of two control tower operators. As far as eyes and ears are concerned, they still need a 1st class certificate in Germany. That's why they give some trouble to the expert board.

The first operator, 44 years old, is myopic on both eyes with an uncorrected visual acuity of R 0,05 and L 0,1. He doesn't even meet the 3rd class standards. But with glasses he can be corrected to R/L 1,0.

We have to ask ourselves, how he ever got his first certificate, but nevertheless he has been working so far without the slightest difficulties in air traffic control. In our opinion it would be sufficient for control tower staff to evaluate only the corrected vision. The reason for considering the uncorrected vision in flight crew is to provide flight safety in case of loosing or breaking spectacles, for instance in severe turbulence. As there are hardly any thunderstorms or air-pockets in a control tower environment to be expected uncorrected vision is of no importance:

A 2nd control tower operator, 46 years old, reads only 0,8 in one eye, with the other 1,0. He also doesn't meet 1st class standards.

As air traffic control personell nowadays works mainly with two-dimensional displays, binocularity no longer is of very much importance for this duty. Therefore the board issued a waiver. Anyhow, more important for display reading is near vision, not only for ATC-staff but also for aviators. The current standards regulations for near vision are given in the next slide (fig. 1).

But do we need special requirements for near vision at all, as near-vision corresponds exactly to the distance visual acuity, if only appropriate reading glasses are used? It's just a matter of mere calculation.

The next expert boards case leads to the problem of contact lenses in aviation. The 34 years old applicant wanted to become a parachutist. Due to myopic astigmatism his uncorrected vision is 0,03 in both eyes. German standards however require 0,1 uncorrected. German Air-force as well as US civil standards give no inferior limits as long as the corrected visual acuity is 1,0.

But we have to consider that especially in parachuting wearing of glasses may be a problem. The visual field will be constricted, the glasses may break or get lost during the jump. Then a visual acuity of only 0,03 is not sufficient to estimate the proper landing position.

It is extremely difficult to estimate the minimum visual requirements for different flight conditions. The current US-minimum of 0,1/0,1 for 2nd class qualification seems to be fairly low. A detailed experimental study in cooperation with the Institute of Aviation Medicine in Fürstenfeldbruck is planned.

To come back to our parachutist, he instead could wear contact lenses to remain his visual field. But at least in Germany these have to be soft lenses. As you can see in the next slide (fig. 1), contact lens use in aviation also is diverse in national aviation requirements. In Germany hard contact lenses can be worn in all cases where glasses are required except for parachutists and stunters. They have to use soft lenses. But this only applies for civil aviation. Strangely enough, the "Bundeswehr" and also the US Air-force don't allow contact lenses at all. As we have learnd today, contact lenses could be the best only possible optical correction in connection with night vision goggles. The US civil regulations say that "Experience had indicated no significant risk to aviation safety in the use of contact lenses for distant vision correction... However contact lenses that correct near visual acuity only or that are bifocal are generally not considered acceptable for aviation duties." This certainly is a good description and a wise decision.

Interesting in this connection is the contact lens for aphakia correction. In US civil aviation contact lenses explicitly have to be worn in these cases because of the extremely narrow visual field when using glasses for aphakia correction. In Germany the "Gutachterausschuß" again would have to decide as uncorrected aphakic vision is below the 3rd class limit of 0,1. US Air-force rejects applicants with uni- or bilateral aphakia in general.

In cooperation with the Institute of Aviation Medicine, DFVLR, we have done some studies concerning contact lens use during flight conditions. We especially investigated g-tolerance, the compatibility of CL in low atmospheric humidity of 10 % and the formation of gas-bubbles under decompression to 16.000 feet altitude. The results revealed the excellent tolerance of CL in flight conditions (5).

And what about intraocular lens implants? They are not mentioned at all in German requirements, neither civil nor military. In US civil aviation the applicant needs a Statement of Demonstrated Ability (SODA) or other written evidence that he has been cleared by the FAA. If he meets the visual acuity standards, there are no restrictions to issuance. In the US Air-force implants are rejected again (fig. 1).

Again an example from the practice: A 37 years old fighter pilot developed a traumatic cataract after perforating scleral lesion with intraocular foreign body. An extracapsular cataract extraction was performed with intraocular lens implantation (6). The postoperative visual acuity without correction was 0,8, with glasses 1,2. After extensive discussions a waiver was issued. He had no problems in doing his duty as fighter pilot. Monocularity is another problem in medical standards. Detailed provisions exist in German and US civil aviation to allow the one-eyed pilot to demonstrate his ability to compensate for the loss (fig. 1).

In Germany only a 3rd class certificate can be issued for one-eyed applicants whereas in the USA there is no restriction to private pilot's license. With flight experience the airman may qualify for additional pilot certificates. In the "Bundeswehr" and in US Air-force monocularity leads to rejection of the examinee. Another example quite difficult to be decided by the expert board:

The 46 years old pilot was qualified 2nd class since 1975, with 2.300 hours flying time. However, due to strabism in childhood she had amblyopia with a best corrected visual acuity of 0,1 in the left eye, the other eye reached full vision. Therefore she practically was monocular, which means only 3rd class qualification. But special issuance by the "Gutachterausschuß" was given in the end, for she had definitely demonstrated her ability.

Our last example deals with glaucoma: A 48 years old pilot suffered from open angle glaucoma. There was no loss of visual acuity or visual field and the intraocular pressure could be kept under adequate control by eye drops. In the "Bundeswehr" and US Air-force as well as in German civil aviation up to now any kind of glaucoma is cause to deny certificate issuance. In German civil aviation however the requirements are about to be changed to then exclude only a noncompensated glaucoma. Only the US civil regulations take the advantages of modern glaucoma surgery into consideration: Special issuance by the FAA is made on an individual basis, if iridectomy in narrow angle glaucoma or a fistulating operation in open angle glaucoma has been performed satisfactorily over three months prior to application (fig. 1).

We could still go on with our examples, but I think the most important problems have been pointed out so far. Concerning color vision and visual field, a comparison of the national requirements here is given too (fig. 1). We wanted to show first of all, that due to either modern possibilities of ophthalmological surgery (cataract or glaucoma) or due to new navigation instruments and displays (near and distant visual acuity) most of the regulations certainly have to be revised and adapted to modern requirements.

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Figure 1: Comparison of the national aviation regulations

	F A A	German civil	Bundeswehr	US Air-force
Visual acuity:	I/II: s.c. 0,2 c.c. 0,7 III: s.c. no limits c.c. 0,6	I/II: s.c. 0,3 c.c. 0,7 or 0,5/1,0 III: s.c. 0,1 c.c. 0,5	I: s.c. 0,5 c.c. 1,0 II: s.c. 0,3 c.c. 1,0 III: s.c. no limits c.c. 1,0	I: s.c. 1,0 IA > 21 years: s.c. 0,1 c.c. 1,0 II: s.c. 0,1 c.c. 1,0 III: s.c. 0,05 c.c. 1,0/0,7
Near Vision:	1st class 1,0 no sp. requ. for II/III	all classes no sp. requ.	all classes no sp. requ.	I: s.c. 1,0 IA > 21 years: s.c. 0,5 c.c. 1,0 II: s.c. 0,1 c.c. 1,0 III: s.c. no stand. c.c. 1,0/0,7
Contact Lenses:	all classes no limits necessary for aphakia	all classes no limits except for parachute and stunting	all classes not allowed	I-II: rejected III: "waiver" poss.
IOL-Implant:	not mentioned SODA necessary	not mentioned	not mentioned poss. with "waiver"	rejected
Monocularity:	no restrictions waiting time 6 months	I/II: no issuance III: poss. after 1 year	I-III: no issuance	I-III: rejected
Glaucoma:	special issuance	no issuance	no issuance	rejected
Color-Vision:	I: normal c.v. night flights can be excluded	I-III: AQ 1,3/0,66 III: signal test poss.	I-III: AQ 0,7 - 1,4	I-III: normal color vision
Visual field:	I/II: normal v.f. III: no severe diseases of the eyes	all classes loss up to 20°	all classes loss up to 15°	I-III: peripheral loss up to 15°

DISCUSSION
Paper 11

11. Dr Draeger presented by Dr Wirt - Germany - Particular problems of Air Worthiness from an Ophthalmological View.

Brennan UK: It is a subject in which I am very interested and on which I will be talking later. As regards contact lenses we ran a trial and the results of the trial appeared in the January 1985 edition of Aviation Space and Environmental Medicine. The Flight Acceptability of Soft Contact Lenses: An Environmental Trial. Brennan, D.H. and Girvin, J.K. We fitted a number of subjects with contact lenses and they came to Farnborough where they were subjected to the environmental stresses. We subjected them to every adverse stress we thought relevant and the lenses behaved well, so I would agree with you up to that point. Something less than 40 subjects were fitted with soft contact lenses or either 50% or 75% water content and we encountered, in this limited sample, two cases of corneal ulceration. One was a limbal ulcer which fortunately had no consequence to vision being peripheral, but we also had one central corneal ulcer which required a keratoplasty. Fortunately the pilot is now flying again, but that was a very high incidence of infection. Soft contact lenses also require a great deal of maintenance and perhaps in the field it would not be advisable to issue them. I am thinking, for example, of a Harrier detachment out in rough terrain. So on that basis we in the RAF, currently, do not issue contact lenses to aircrew except in exceptional circumstances where they are required for pathological reasons. We also had one instance and this happened on the ground, of a volunteer suffering an FB behind his contact lens and this was extremely painful as the contact lens moved the FB. The soft contact lens may also pick up atmospheric pollutants. We have not done a trial with chemical warfare agents to see whether there would be a slow release, but I think it might well happen. On that basis we do not accept contact lenses. Changing the subject, you showed somebody with an intra ocular lens, could you be sure of the stability of that lens under high G forces, say with a rapid decelleration or an ejection. I also noticed that he had a very large peripheral iridectomy, in fact it was far more than peripheral it was almost extending to the iris margin; does he not have trouble with a double pupil?

Wirt GE: Concerning your first description of the two complicated cases with contact lenses, we all know these cases from contact lens wearers outside aviation. There are some millions of contact lens wearers thoughout the world but most of them do not suffer from corneal ulceration until after years of continuous contact lens wear. An ulcer will not happen within hours and preceding any serious corneal damage the affected person will feel some pain, some irritation, so in general he will remove the contact lens long before an ulcer occurs. From the first lesion of the corneal epithelium through infection to ulceration takes, even in rapid cases, some days, so I am really surprised how these people could develop an ulcer unexpected and unsupervised. Normally a subject will take them out as soon as he feels the first little irritation and nothing happens. We have never seen troubles from contact lenses different from troubles in general life. As far as this case with an intra ocular implant is concerned it is some years back, and I must explain that there was a period when intra ocular implants were fixed inside the eye by little loops attached to the chamber angle and this led to serious complications 20 years ago. The next step and this is what you saw in the slide, was fixation by little loops behind the iris, the optical part being in front, this being the style ten years ago. It was a seriously damaged eye which was rejected by different departments for operation at all. When we saw the patient he showed a marked irritation from the opened anterior surface of the lens, lens material had come into the anterior chamber. We were worried by posterior synechiae and irritation and this is what led to a large iridectomy, I admit this to Dr Brennan of course, we were lucky that the eye cleared with the next two or three days and that implant stayed in place. Using precise ultrasonography we ended up with a very good uncorrected vision of 0.8 which is rare even in an experienced department, usually you need a lens to restore full vision. This is what finally led the Bunderswehr to let him fly again and to my knowledge he has continued his pilots service without serious problems. A modern intra ocular implant and the one you saw has a weight of about 5 mg compared with the normal eye lens weight of about 200 mg, is very light. This is a point we have discussed with General Burchard, we have not yet put patients with implants on the centrifuge or even on the ejection seat to give them 10 or more G. I am sure nothing will happen to them as they would lose their natural lens before the implant, as it is heavier and with the new technique it is perfectly fixated into the capsular bag. We have not proved this experimentally, so far, but we had the same questions and also the same doubts of course. It would be a very good idea to try to check this with your assistance General Burchard.

Brennan UK: Yes, I think that somebody has to check whether these lenses will stay in position. I take your point, of course, the lenses you showed are not used now. It is posterior chamber lenses which are fitted with polypropylene springs into the ciliary sulcus and these should be much better retained but of course the anterior capsule has largely gone, you only have the posterior capsule so perhaps in a sudden decelleration - I don't know what would happen. Yes, we were unfortunate to have the incidence of infections we had, on a percentage basis it was very high. Perhaps when new lens materials come along which require less maintenance we may adopt them. I don't know.

Santucci FR: Within the French Air Force we adopt the same attitude as the British. Concerning contact lenses it is true that in a decompression chamber the bubbles may not be so harmful, but these contact lenses may have to be used in an operational environment. If you have a helicopter in the field which is far away from its base it is often difficult for the pilot or crew to get food, how are they going to maintain the contact lenses in this situation? A possible solution would be to have disposable lenses. Now, regarding the lenses which will be removed when they become painful to wear. I remember the case of one of my younger colleagues, an ophthalmologist, who went to sleep wearing his soft lenses, the next morning he developed a perforating ulcer. Fortunately he recovered after surgery. Now concerning the intra ocular implant, 5g is very light, but with a 9G acceleration it becomes 45g. What happens to the cornea irritated by the loops of a fixation system? Before we change standards, experiments are necessary

and in France we are going to carry out experimentation on animals before risking a human eye. Last point, concerning the colour standards, I feel that we decided too quickly to revise them. There is a change, a development, in the displays in military and civil aviation. Multi hued arrays will be used and a lot of money is being spent on the CRT tubes, meaning that we require the whole range of colours. We may have more flexible standards, but let us wait a bit until we know what would be the performance of someone who does not see the colours. Would such a person be able to see a multi colour tube? It is all very well to revise or review standards to accept a larger number of pilots but what are the consequences? I may be wrong but I feel it is too early to change standards. In any case there is no war at present, we do not need so many pilots so for the time being lets play safe. Now concerning the work of my civil colleagues who do not work in the Air Force, they should recommend their pilots to remove their soft lenses and use spectacles when they are on civil flights from Paris to New York, for example.

Burchard GE: I have one other comment about the implant, it was a very difficult decision for us to have the first pilot flying about 9 years ago. Now we have three pilots flying with artificial lenses. You have, as far as the G load is concerned, to consider that the new material of the implant has about a density of 1.0, so the lens is suspended within the eye. If you have a density of less than 1.0 the lens will tend to float upwards under the G load and if it has a density above 1.0 it has a tendency to go down. So the weight actually does not have any impact on the position of the lens if it has a density of 1.0, and as far as our pilots are concerned they have had no difficulty in flying high performance aircraft.

Brennan UK: I would just like to add that if you were unlucky enough to suffer a pyocyaneus infection it would take very little time at all to perforate, but having said that of the people that suffered the ulcers, at least one of them complained rapidly and was treated quickly and the ulcer was contained. I cannot speak for the other man as I did not see him but it is possible, although I do not know, that he was slow in complaining, some people are more stoical than others and will take longer to seek assistance.

Computer Visual Simulation of Contrast Sensitivity Deficits Induced by Laser and Chemical Antidote Exposure

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SUMMARY

Training in some complex combat-related tasks may produce a degree of transient visual impairment which may simulate what could be expected in combat. This paper presents a method for simulating visual impairment produced by potential combat conditions. The use of a computer to both digitize and store as well as produce the simulated image has provided an ideal tool for research. The degree of realism provided by such simulation offers suggestions for development of more realistic training techniques.

The ability to represent a complex visual image along a unitary dimension and relate this dimension to target acquisition criteria is critical to military training concepts. Recent experiments (1) have suggested that the physics of form and human spatial vision are uniquely related to the spatial frequency domain. Small changes in the amplitude of selective spatial frequencies can have significant effects on human form vision (2).

A scheme to represent a complex target along a single spatial frequency continuum was first proposed by Johnson (3). The Johnson criterion relates the number of cycles in a square wave grating (black bars periodically alternating with white bars) required for either detection, identification, or recognition, to complex military targets as a function of target range. Complex military targets can be scaled with respect to the number of cycles required for either detection, identification, or recognition.

While the Johnson criterion (3) is adequate for scaling high contrast stimuli in a reliable manner, it is neither parsimonius with current physiological mechanisms underlying human spatial vision nor adaptable to characterizing how the perception of complex images might be degraded by exposure to noxious battlefield conditions.

Many recent experiments (2) indicate that mechanisms underlying spatial vision are selectively altered with regard to their ability to represent the spatial frequency domain. Such degradation in the neural mechanism of spatial vision is not easily represented by changes in the number of cycles required for a visual response.

Image degradation which might be produced by potential battlefield exposure conditions can be simulated by modulating the spatial frequency content of a complex image using data derived from the actual amplitude modulation induced by experimental procedures. In this paper, spatial frequency contributions have been modified according to the results of experimental data to obtain the inverse Fourier transform of a complex image.

METHODS

A computer interfaced with a video frame buffer was used to produce Fourier filtered images. The frame buffer used stored images in a 256 by 256 pixel format with 64 shades of grey (4). A two-dimensional fast Fourier transform (FFT) was used to alter the spatial frequency content of a complex image in accordance with changes that had been induced in contrast sensitivity experiments. The original image was filtered by reducing the signal amplitude contributions at selected spatial frequencies in direct proportion to losses obtained in contrast sensitivity at corresponding spatial frequency points. An inverse FFT was then performed and the filtered image displayed on a CRT and stored on hard disk.

Data from three contrast sensitivity experiments - the acute effects of Q-switched pulsed laser exposure (5), benactazine (6), and atropine (7) - were used to derive degraded images in correspondence with the previously obtained contrast sensitivity data.

RESULTS

Contrast sensitivity data, replotted as a percentage of the baseline contrast sensitivity for acute laser exposure (5) and for benactazine (6) are shown in Figure 1. Changes induced by atropine (7) were very slight, varying between 95 and 98% of baseline

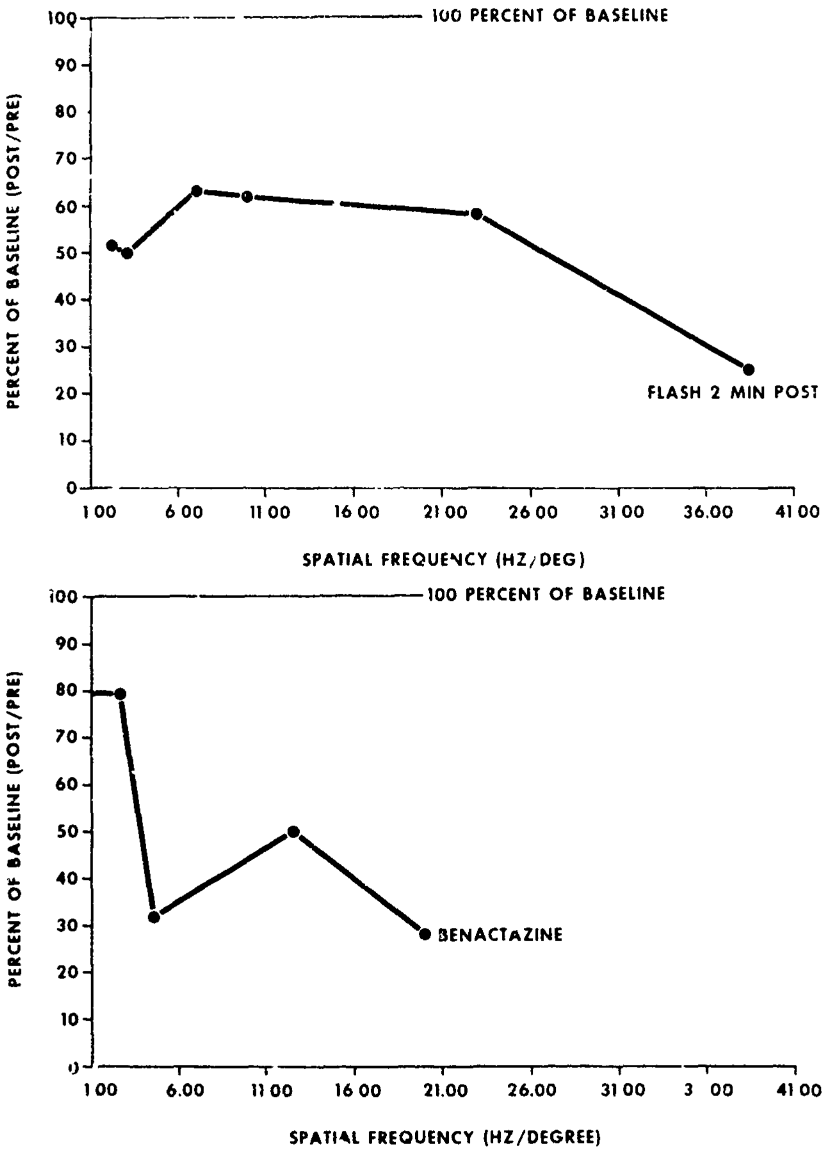

FIGURE 1. Contrast sensitivity functions from laser flash and benactazine (5,6) experiments replotted to reflect loss in contrast sensitivity over the spatial frequency spectrum relative to baseline contrast sensitivity.

contrast sensitivity measured over the same spatial frequency range as used for benactazine. Inverse transformed images based on the data from each of these experiments are shown in Figure 2a,b,c,d. The upper left panel is the normal digitized image (2a). In the upper right panel the image has been transformed according to changes induced by acute laser exposure measured at 2 minutes post-exposure. The lower left and right panels (c and d) correspond to the benactazine and atropine measured contrast sensitivity changes. Because the effect of acute laser exposure is nearly uniform over the measured spatial frequency region. the image (b) appears to be reduced in overall contrast, unlike that of the same image transformed for the benactazine deficit (c). In this case, a definite blurring of the image is perceived, as fine spatial frequency loss is relatively greater than losses at the lower spatial frequencies. Minimal change in the perceived image qualities is observed for the atropine (d) condition.

DISCUSSION

In this paper, we have demonstrated that contrast sensitivity data can be utilized to create degraded images that correspond to the measured changes obtained in spatial vision experiments. With this procedure, complex images can be modified to reflect the measured visual response to various noxious environmental conditions. More importantly, with such procedures, any image that can be digitized, can be modified and used in

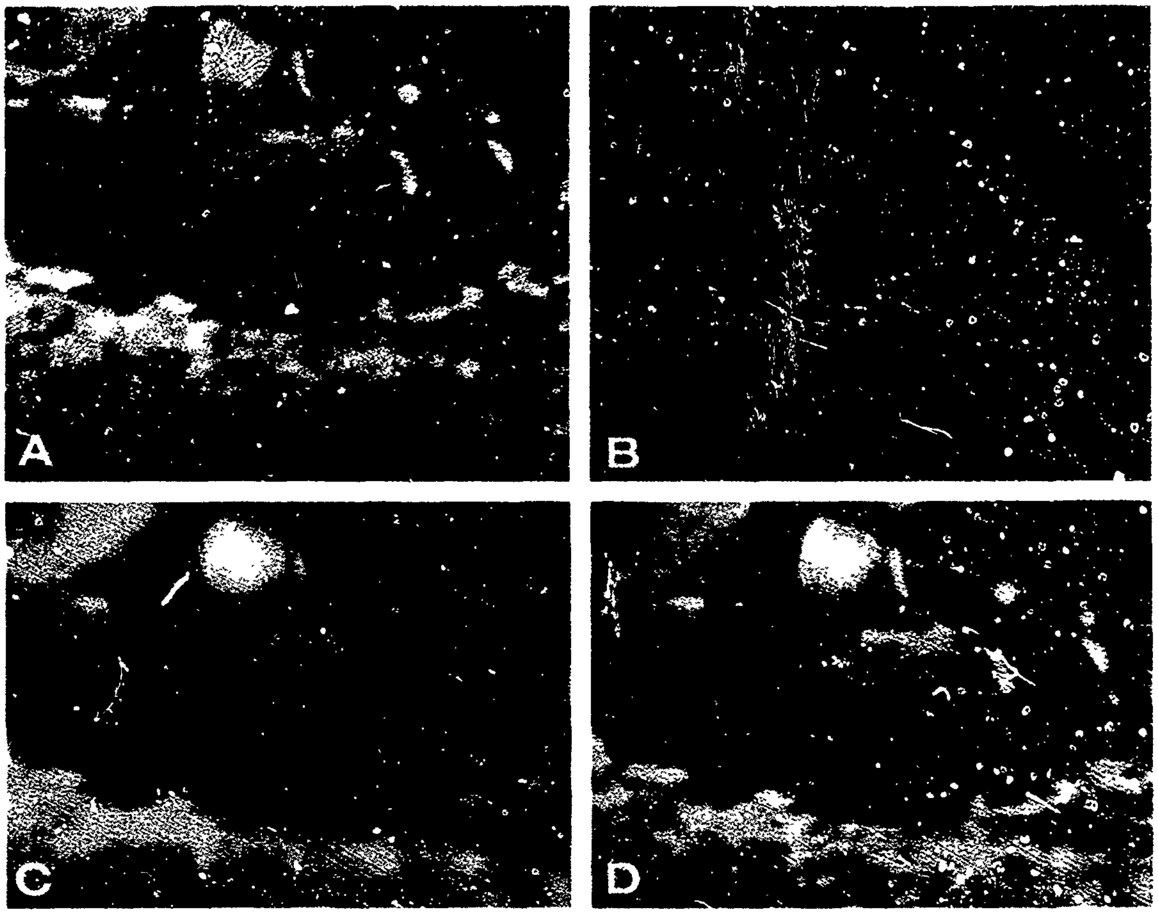

FIGURE 2. Computer generated images.

specific training scenarios. This method extends our ability to characterize complex stimuli by allowing both normal high contrast as well as degraded images to be represented along the spatial frequency dimension. The knowledge that certain exposure conditions might blur vision while others might simply alter the overall contrast of a complex scene is information that could be provided safely only with the aid of the present technique for characterizing the effects of noxious environmental conditions on spatial vision.

Finally, for the development of effective combat training, incorporation of the degradation technique provided here offers a viable alternative to training procedures requiring adverse environmental conditions capable of producing moderate transient physiological effects. Such training simulations can be readily adapted by the Army in both basic and advanced courses to prepare for the soldier's ability to be successful in combat despite minor or major alterations in vision.

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NEW GLASSES FOR PRESBYOPIC PILOTS

by

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The variety and complexity of visual demands in cockpit environment is increasing. The vertical and lateral arrangement of flight information systems, in addition at different distances makes observation time consuming, since movements of gaze combined with accommodation are slower than movements alone. This difference is due to a delay of accommodation of about 250 msec. (HARTMANN, 1980). Flight information systems therefore should be closely concentrated, whenever possible. This applies to the young pilot who has to share his attention between cockpit, air space and observation of the enemy, and even more so to the senior, which means presbyopic pilot.

Presbyopia is a physiological condition starting by an age of about 40 and increasing steadily with age until accommodation ceases around 55. This means that the naked eye is not able to read instruments and charts in near distance. This problem is not only of theoretical interest and may effect even a younger pilot: According to the normal distribution of myopia and hyperopia in a population there is a certain percentage of "latent hyperopia" with full distant vision. In this case accommodation is continuously necessary already in distance viewing and even more so in close range. Reading problems thus become obvious even before the age of 40. The blurred vision begins at close range (I.A.L. Chart, manuals, check-list), later at mid distances (forward instrument panel, center console, overhead panel).
New flight information systems have improved this situation, since the visual information is concentrated in a small area.

In a fighter cockpit the information of the head-up display is projected on to the wind-screen. Therefore the pilot has to share his attention between infinity and the projected image of the head-up display, focussing and defocussing very quickly between both distances, always looking straight. This reaction slows down with age and presents a problem similar to that of an older rifleman who has to accommodate between backsight and forsight for aiming. With beginning presbyopia aiming gets more and more difficult, till the use of a sighting telescope becomes necessary.

In civil airliners still side and overhead panels call for extensive eye movements however. New designs of multifocal lenses are therefore essential for the presbyopic pilot. Especially overhead panels require new, unconventional solutions. Regarding the great difference in cockpit design between a fighter aircraft and a jet-transporter the glasses have to be specifically tailored to the aircraft used to meet all requirements.

In an experimental study an attempt was made to investigate this complex problems and to test certain solutions (DRAEGER et al, in print). A group of untrained presbyopic subjects were asked to perform specifically designed tasks of assembling small parts and were fitted with different multifocal glasses. In three different ranges and different levels, approximately according to the distance in a cockpit (Charts, center console, forward panel, side panel, overhead panel), they had to differentiate and to grasp small electronic elements and to fix them on an electronic plate. The time needed and the mistakes were noted and compared. The evaluation showed much better results for those subjects which had with their glasses the greatest visual field for each specific range and level.

The beginning presbyopic (40 - 47 years) were able to compete with the high performance group when using exactly fitted bifocals.

At the age of 50 trifocal lenses gave the best results, but this group did not reach same level as the high performance group.

The glasses tested were common bi- or trifocals with small reading parts, glasses of the "executive type" with large reading parts and horizontal border and progressive glasses. The best results in both presbyopic groups were found with glasses of the executive type which gave the greatest possible and well defined visual field in each range.

In applying our experimental results to different cockpit condition the following conclusions can be drawn:

1. Pilots with beginning presbyopia are able to accommodate for mid distance. They can control forward panel, center console and a great part of the overhead panel (fig. 1).

   Fig. 1: Schematic drawing: Cockpit and correction areas (A 310)

   They need glasses for the charts, manuals and checklists however. Lookover or a bifocal of the executive type might be sufficient. This is in accordance with WATKINS (1970).

2. Pilots with advanced presbyopia are not able to control these distances without optical aids. Consequently we have to correct three different distances:

   a) Infinity to windshield
   b) Medium distance for forward panel, center console, side panel and part of overhead panel
   c) Near distance for part of the overhead panel, checklists, manuals and charts.

The dimension of a fighter cockpit is relatively small, it is very compact. Therefore the high visual demands result more out of the high speed and the necessity of fast reception of the visual information. For a presbyopic fighter pilot we would advice special trifocal glasses with a distance part and midrange part, both of great extension. This allows to visualize the pedistals on his right and left side, as well as forward panel and the aiming display. A relatively small, but well centered reading part for the charts should be sufficient.

In a helicopter cockpit the problem for the presbyopic pilot is different. Here we have to consider that the pilot has to lower his gaze to control his instrument panel in near distance and also for looking into distance out of the lower windows. Therefore such glasses need a distance part at the bottom as well as at the top. The situation in transport aircraft or commercial airliners is similar.

The extension of the various panels is large. The pilot is almost surrounded by instrument panels in different distances. Even in very modern cockpits with new integrated flight information systems the pilot has to face high visual demands. Especially the overhead panel requires an unphysiologic tilt upwards and sideways of the pilot's head combined with accommodation.

The usual vertical arrangement of the different refractive powers within multifocal lenses is not adequate for pilots of these aircrafts. To diminish the movement of gaze they need glasses with lateral asymmetry to allow an easy overview of forward panel, side panel, center console and overhead panel. The upper part of the lens needs therefore an additional reading part and preferably a certain lateral asymmetry. This decentration keeps the distant part relatively unaffected. Control of the forward panel and of the center console requires also a midrange part with a lateral asymmetry becoming wider towards the right side for the pilot. This leaves enough space for a well centered reading part for the charts (fig. 2).

Fig. 2: Schematic drawing: Cockpit seen through special glasses with lateral asymmetry

One has to consider that the glasses for the copilot should show the inverse asymmetry. It is of course necessary to fit those glasses in accordance with the seat position and the eye indicator, or following the glare shield for the distance part (BACKMAN & SMITH, 1975).

This design is superior to using a special bifocal with a flip down attachment for overhead panel vision (HARPER & KIDERA, 1968). The use of progressive glasses, as recently recommended (BYREN, 1984) may cause problems because of the distortion of the image looking sideway.

In summary we recommend to correct presbyopic pilots very early with bi- or trifocal lenses, preferably of the executive type, for optimal performance and to avoid discomfort, asthenopic problems and possible hazards. We recommend for the modern commercial aircraft cockpit special tri- or quadrifocal lenses with lateral asymmetry according to the specific requirements (fig. 3).

Fig. 3: Special glasses for the presbyopic pilot of a commercial airliner

The further development of design of such highly specialized occupational environment should be based on human abilities and limitations. The optical demands should be considered from the very beginning.

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Figures:

Fig. 1: Schematic drawing: Cockpit and correction areas (A 310)

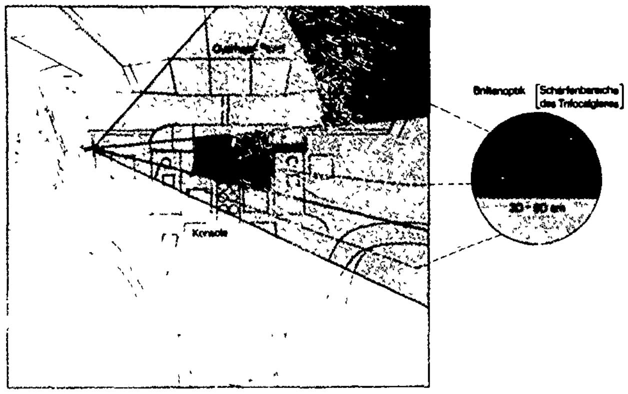


Fig. 2: Schematic drawing: Cockpit seen through special glasses with lateral asymmetry

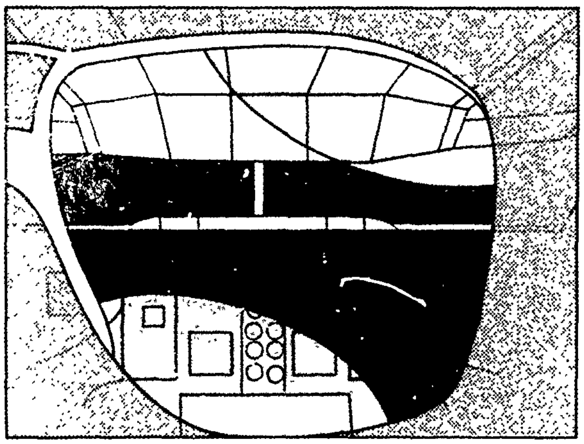
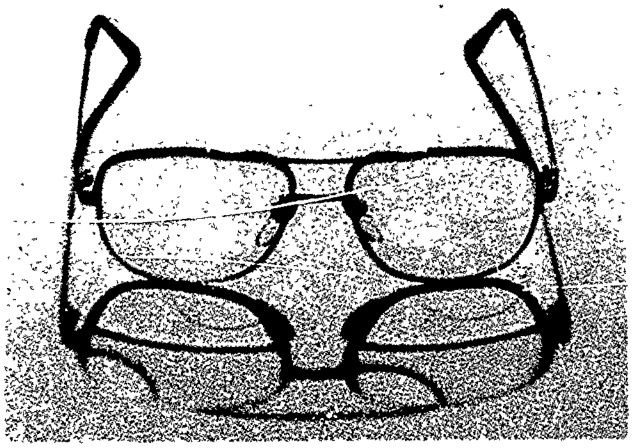


Fig. 3: Special glasses for the presbyopic pilot of a commercial airliner



CONTACT LENSES FOR PILOTS AND AIRCREW IN THE SERVICES

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SUMMARY

After working for five years in the Contact Lens Department of Moorfields Eye Hospital in London and after fitting and monitoring forty volunteers in the RAF Aircrew Soft Contact Lens Trial (ASCL Trial), it is the opinion of the author that High Water Content Soft Contact Lenses, or Silicone Lenses, used as Extended Wear Lenses, are the only contact lenses which are suitable in an Aircrew Service Environment. The fitting and monitoring of such lenses must be carried out by experts in the field of contact lenses.

Hard Contact Lenses are a potential serious hazard in the Aircrew Service Environment.

Not all aircrew members, requiring glasses to obtain best visual acuity, will be suitable for using such contact lenses and these persons must continue to wear glasses when flying.

ASCL Trial	=	Aircrew Soft Contact Lens Trial
Dk	=	Oxygen transmissability factor
		(cm^2/sec) (mls O_2/ml X mm Hg) at 21^oC or 35^oC
PMMA	=	Poly Methyl Methacrylate
VA	=	Visual Acuity
CL	=	Contact Lens
W/T	=	Wearing Time
FB	=	Foreign Body
QRA	=	Quick Readiness Alert
CFS	=	Corrected Flying Spectacles
AR5	=	Aircrew Respirator NBC No 5 Mk 2

INTRODUCTION

Since around 1950 Contact Lenses have become an accepted optical aid in the functional replacement of spectacles.

Out of a population of 218 million in the USA, 115 million wear spectacles. Of this number 12 million (13.8%) were wearing Contact Lenses in 1981.[1]

An estimated 20% annual increase in Contact Lens wearers was expected by the large contact lens manufacturers in the USA in 1981.[1]

Not unnaturally aviators, who have to wear corrected flying spectacles when flying, are very keen to emulate their fellow citizens and wear Contact Lenses in place of spectacles when flying.

What should the attitude of the medical adviser be in this context?

Contact Lenses Available

The Scleral or Haptic Contact Lens covers the anterior surface of the globe. It is large, uncomfortable, gives a variable visual acuity and air bubbles beneath the lens are common place.

It is entirely unsuitable for aircrew.

Such lenses, though, have a valuable role to play in ocular therapy

The Micro-Corneal Hard Contact Lens

Such a lens is composed of PMMA material or an Oxygen Permeable Polymer mixture. The majority of such lenses have an overall diameter of 8 to 10 mms and rest on a thin tear film (see Figure 1). A well fitted lens can move 3 to 4 mms on blinking without any loss of VA or discomfort to the patient. Such lenses are Daily Wear Lenses and cannot be worn for longer than 17 hours without the patient developing blurred vision and a painful red eye due to Hypoxia of the Cornea.

The Dk factor for the PMMA lens is zero

The Dk factor for an Oxygen permeable hard lens varies from 3 to 6 x 10^{-11}

The 38% Water Content Soft Contact Lens

The majority of Soft Contact Lenses on the market are of this type. Such lenses are Oxygen Permeable having a Dk factor of $9 - 11 \times 10^{-11}$. The diameter is 12.5 to 13.5 mms. The lenses are comfortable and in suitable cases give good visual acuity. The lens movement of a well fitted lens, on blinking, is 1 - 2 mms. There is a very thin tear film layer beneath the lens (Figure 2). Such lenses are daily wear lenses and should not be worn longer than 17 hours or the patient will develop symptoms and signs of Corneal Hypoxia (viz above).

The High Water Content Soft Contact Lenses

These lenses have a high water content (70 - 80% H_2O) which give them a high Dk factor, eg Scanlens 75, 40×10^{-11} [3]. The diameter is 13.5 to 14.5 mms. The lenses are comfortable, stable and in suitable cases give good visual acuity. The lens movement in a well fitted lens, on blinking is 1 - 2 mms. There is a very thin tear film layer beneath the lens (figure 2).

Such lenses can be worn constantly for weeks to months in suitable cases.

Silicone Lenses

These lenses contain no water but have the highest Dk factor, eg for Silicone Polycarbonate Co-Polymer 160×10^{-11} [4]. The other properties of such lenses are as for the High Water Soft Contact Lenses above. Initially such lenses gave problems because of the silicone material being hydrophobic, and such a lens of pure silicone would have a zero wetting facility and therefore did not permit a pre-lens tear film to form. Therefore, the surface is specially treated to make the material hydrophlilic.

THE DISADVANTAGES OF SPECTACLES WHEN FLYING IN SERVICE AIRCRAFT

(a) Limitation of field

(b) Glare/reflections

(c) Extra optical impediment to visual acuity

(d) Movement on oxygen mask

(e) Problem of integration with other optical aids

(f) Misting

(g) Lenses can flip out

(h) Lens very close to the eye under the AR5 respirator

THE CONTACT LENSES WHICH CAN BE A HAZARD TO SERVICE AVIATORS

(a) All Hard Contact Lenses whether made from PMMA or Oxygen Permeable Polymers, rest on a thin tear film on the surface of the Cornea.

A well fitted hard contact lens is expected to be mobile on the cornea. With each blink of the lids the tear film is pushed out from beneath the lens and the lens moves. On opening the lids fresh tear fluid moves back under the lens and the lens returns to a central position on the cornea again.

This exchange of tear fluid and lens mobility on the tear film is normal for a well fitted hard contact lens.

However, it also means, as any wearer of hard contact lenses or CL Practitioner will tell you, that sudden whole body movement, eg playing Squash or landing heavily on the feet, can result in one or both lenses becoming dislodged and/or falling out of the eye. For the civilian CL wearer this entails stopping the activity which was the cause, and moving the lens or lenses back into position, or searching the floor for the CL which has fallen out.

For the Aviator such a situation is far more serious.

If the hard CL falls out due to vibration or sudden G, he then has a hard FB loose in the cockpit.

He will have lost vision whether the lens has come out or become dislodged and still within the lids. Even if only one lens has dislodged the reflex tearing in the fellow eye will hinder good vision. All this will be happening at a time when the 'jolt' that caused the problem needs the aviator's full attention and skill - but he is distracted by his eye problem and cannot see to solve the difficulty or take remedial action. This is a major Hazard Situation where the aviator, his passengers, his plane, and any aircraft in the immediate vicinity could be at serious risk.

A hard contact lens has a limited wearing time of 'all day'. Overwear results in Corneal Hypoxia with Corneal oedema (blurred vision) and a painful red eye. These symptoms and signs can develop quite quickly if the 17 hours (all day) W/T is exceeded. The same applies to the Oxygen Permeable Hard Contact Lenses. There are newer O_2 Permeable Hard Contact Lens Polymers coming on to the market where the manufacturers claim they can be used as Extended Wear Lenses. These lenses are still being assessed and their true value will need at least a 3 year follow-up.

For the Service Aviator, and I would suggest all Aviators, Hard Contact Lenses should NOT be used because of:-

(1) The possibility of the loss of the lens or dislodgement of the lens.

(2) The possibility of Overwear which often cannot be avoided due to Service duties. For example, 'Long Haul Flights with Re-Fuelling in Flight', and Diversions from the Base Airfield at the end of a Sortie.

(3) The possibility of a Foreign Body becoming lodged under the Hard Contact Lens. This can cause acute discomfort with reflex tearing in the fellow eye, resulting in reduced VA and distraction from the primary flying role.

(b) All Soft Contact Lenses of Around 38% Water Content

These are Daily Wear Soft Contact Lenses. Such Lenses form the majority of Soft Contact Lenses on the market today. These lenses are comfortable to wear and 'cling' to the eye due to the contour and shape of the lens fit with a minimum tear film beneath the lens. These lenses are stable on the eye and it is rare for a FB to lodge beneath the lens because of the fitting characteristics. A FB beneath such a Soft CL is almost invariably due to the FB getting on the inner surface of the lens at insertion.

When a FB does exist under a Soft CL the wearer is conscious of it but it is far less distressing then the FB under a hard CL (Figure 3).

These lenses are not considered suitable for Service Aviators because their W/T is limited to 'all day' or 17 hours. Overwear will result in Hypoxia of the Cornea with blurred vision and a red painful eye.

In the Service environment the Aviator cannot be guaranteed access to his cleaning materials and to being able to remove his lenses within 17 hours.

Examples are:-

(1) Long Haul Flights with Re-Fuelling in Mid-Air and

(2) Diversions from Home Base at the end of a Sortie and

(3) Aviator fully kitted on QRA who then becomes airborne.

THE CONTACT LENSES WHICH HAVE A ROLE FOR SERVICE AVIATORS IN THE FUTURE

One of the lenses used in the ASCL Trial in the RAF was a High Water Content Soft Contact Lens - the Scanlens 75 Lens. In the trial it was compared with a 50% Water Content Lens - the Snoflex 50 lens. The latter lens was not suitable because of its limited W/T, ie not longer than 48 hours and most volunteers could only use it as a daily wear lens.

Both lenses proved eminently satisfactory in the environmental tests carried out by Dr Brennan at the RAF Institute of Aviation Medicine, Farnborough[6].

The following environs were tested:-

Hypoxia

Rapid Decompression

Pressure Breathing

Vibration

Acceleration

Climatic

Aircrew Respirator NBC No 5 Mk 2

The subjects were exposed to the most extreme adverse environmental conditions considered likely to be encountered by military aircrew in flight.

Seventeen volunteers attended the RAF Institute of Aviation Medicine for all or part of the environmental schedule.

In all instances the visual performance of aircrew wearing the soft contact lenses being used in the ASCL Trial did not differ from their performance when wearing CFS, and was not degraded by any of the environmental stresses.

The visual performance of subjects wearing Scanlens 75 (8 subjects) did not differ significantly from those wearing Snoflex 50 (9 subjects).

As mentioned above the Snoflex 50 lens was only tolerated as a daily wear lens. The Scanlens 75 lens is now being used as an extended wear lens, ie Wearing Time 14 - 28 days (continuous wear) and out for 24 - 48 hours. When the lenses are left out and the volunteer uses his glasses there is no drop in visual acuity on returning to the use of glasses. This is most important when comparing such lenses with hard contact lenses - where 'spectacle blur' can remain for days/weeks when the patient goes from wearing hard lenses to spectacles. This is yet another reason why aviators in general should not be allowed to fly wearing hard contact lenses. If he has to remove his hard contact lenses for any reason and puts on specatcles he will have 'blurred vision'. All the volunteers were started on a daily wear basis. This was to ensure they developed confidence in lens handling and maintenance. Not all of the volunteers accepted this and 14 gave up because of the tedium of lens care (as Daily Wear Lenses).

In the course of the clinical assessment we measured Tear Flow (Schirmer's Test), the osmolality of the Tear Fluid and the Na/K Ratio in the Tears, on all the volunteers before and after issuing them with contact lenses. The Na/K ratio was measured by Dr A Winder and Dr Gass at the Institute of Ophthalmology in London.

It was hoped that a retrospective study of the results might enable us in the future to elicit those persons who would be unsuitable for using extended wear soft contact lenses, prior to fitting. Tables 1 to 3 compare the results for the Scanlens 75 lens. The only significant finding was that those with a poor tear production, though completely symptom free, were not able to wear their high water content soft contact lenses as extended wear lenses. There were 4 such cases.

The Scanlens 75 lens was found to be suitable for use as an extended wear soft contact lens.

Remaining in the trial we have 18 volunteers. These are using the lenses as extended wear lenses - worn continually for 14 - 28 days at a time. Of these volunteers two (doctors) are using the Lunell Soft Contact Lens as a trial of a different High Water Content Soft Lens. One (doctor) is working in the Decompression Chamber at IAM and being continually exposed to the stresses of the Decompression Chamber with no adverse effects. One (doctor) is in charge of the Centrifuge Unit at IAM and has himself been regularly conducting tests (unrelated to the ASCL Trial) in the gondola of the centrifuge under high G with no adverse effects as far as his Scanlens 75 Soft Contact Lenses are concerned. One (pilot) has had a cataract removed and wears a Scanlens 75 lens as an extended wear lens with no adverse effects when flying a Jet Provost and pulling 4 - 5 G.

All volunteers who are using the Scanlens 75 like using these lenses because of the good VA, the much improved field for flying and viewing instruments, and the stability of the lens on the eye.

Other High Water Content Soft Contact Lenses may well be suitable, but we have no experience of them.

Likewise,Silicone Soft Contact Lenses are also expected to be suitable in a Service Aircrew environment.

WHAT PROBLEMS MAY BE ENCOUNTERED WITH THE IDEAL SOFT CONTACT LENS FOR A SERVICE AVIATOR, AND HOW MAY THEY BE PREVENTED

(a) As with all persons being fitted with a high water content soft lens, not all are capable of handling such soft delicate lenses (inserting, removing and cleaning). They do not have the temperament or the patience or they are unwilling to follow the strict hygienic requirements necessary and do not follow the instructions given in the care and maintenance of their lenses. Such persons can only be eliminated after a reasonable trial period.

These cases are '<u>failure to handle and maintain</u>' and must return to using spectacles when flying.

(b) Having successfully fitted a subject who is handling and caring for his lenses correctly, the following conditions must be guarded against at regular reviews by an ophthalmologist or experienced ophthalmic optician with access to a Contact Lens ophthalmologist:-

(1) <u>Viral Superficial Punctate Veratitis</u>

The subject will usually complain of slight discomfort and there is usually mild ciliary infection around the limbus. See Figure 4. Contact Lenses must be stopped and appropriate therapy instituted. It is most important that Contact Lenses are not used again until the Corneal Epithelium has completely healed. This can take a considerable time.

(2) Early Vascularization of the Cornea

Subject can be symptom free and the eye can appear white and quiet. Figure 5.

This is evidence of Hypoxia of the Cornea. The subject may be over-wearing his lenses, ie wearing for longer periods than instructed,eg 3 months continuous wear instead of one month.

This can be remedied by removing the lenses until the Corneae are clear and then re-checking the lens fitting and reducing the W/T to 1 week at a time. This time can be slowly increased while watching the Cornea carefully.

(3) Keratitis or Grey Infiltrate in Cornea

Subject will usually complain of a slight discomfort in the affected eye. All subjects are repeatedly instructed that, if they have any discomfort or redness, they are to report to the Ophthalmologist i/c within 24 hours. Figure 6 illustrates the typical appearance. One case on the ASCL Trial developed a Corneal Abscess and had to have a corneal graft. He had repeatedly overworn his lenses and he did not report immediately to the ophthalmologist i/c on developing symptoms. The lens wear is stopped and the subject is admitted to hospital for intensive therapy. When the condition has cleared the subject returns to his Contact Lens wear, but the extended wear time is reduced to 1 week and built up slowly again.

(4) Giant Papillary Conjunctivitis

The subject will complain of discomfort, itchiness, and red eyes, and the lens sometimes moves on blinking.

This is due to a sensitivity reaction to the solutions being used to clean the lens (I describe this as small Pap Conjunctivitis) or to the lens polymer itself. The Conjunctiva shows an uneven surface of large papillae. In the early stages they are best seen in the Sub-Tarsal Conjunctiva.

Lens wear must cease and the subject must not return to using his contact lenses until the conjunctiva has returned to a normal flat smooth surface. This may take many months. This is frustrating for the subject because his eyes feel normal. On returning to the use of lenses - a different cleaning regime may be necessary and different type of lens may be adviseable.

(5) Deposits on the Anterior Surface of the Lens

Subject symptom free. Such deposits are due to an accumulation of Protein, lipids, and cell debris. It is a sign of a poor cleaning technique or infrequent adequate cleaning, or the biochemical content of the wearer's Tear Fluid. The latter requires further investigation. When such deposits occur the lens should be discarded and replaced with a new lens. SEE FIGURE 7.

(6) Split or Tear in Lens - Usually at the edge

Subject symptom free. Split or tear can extend and may then entrap the conjunctiva and cause discomfort.

Replace the offending lens with a new lens.

(c) Planned Management and Follow Up for the Ideal Soft Contact Lens as Extended Wear Lens in an Aviation Environment

All such subjects must be under the direct care and supervision of an Ophthalmologist who has considerable experience of Contact Lens cases. Ideally he should have as an assistant an ophthalmic optician, who is also experienced in Contact Lens work.

(1) The subject has a full ophthalmic examination to exclude any previously non-recognised ophthalmic pathology. Any Astigmatism is noted. In our experience a Cylinder of more than 1 Dioptre is not suitable for the S75 lens if best VA is to be achieved. Included in this examination is the Schirmer Test.

In the ASCL Trial 4 subjects had repeatedly very low Schirmer readings, although their eyes were otherwise healthy and they were symptom free. These volunteers, as expected, were not able to tolerate their soft lenses for longer than 10 hours.

The subject is fitted with the selected Soft Contact Lenses and the appropriate lenses are ordered.

(2) The lenses are issued and the subject receives detailed written instructions on care and maintenance and to report within 24 hours if he has any problems.

The lenses are issued as daily wear lenses in the first instance in order that the subject may quickly learn to handle and care for his lenses.

(3) He is reviewed in 2 weeks. If all is well he then uses the lenses for 1 week at a time as continuous wear, and leaves the lenses out for 48 hours (returning to glasses).

(4) He is reviewed in 1 month. If all is well he wears his lenses for 2 weeks at a time, out 48 hours, and he is reviewed in 3 months. He is thereafter reviewed every 3 months or immediately if any problem arises (no matter how small or insignificant it may seem to the subject).

CONCLUSION

It is possible to fit Aviators with an ideal Soft Contact Lens as an Extended Wear Lens but the fitting, the managment and the after care supervision must be planned with great care and the fitters, and ophthalmologists involved, must be experts in the field with a detailed knowledge of the aviator's role, in the aircraft and on the ground.

I would suggest a unified approach to the problem of 'Contact Lenses and Aircrew' (Service and Civilian) is required if we are to avoid unnecessary hazards to men, machines and civilians in the future.

We must always remember that 80% of Flight Information is 'Visually Acquired' (Agard 1978).

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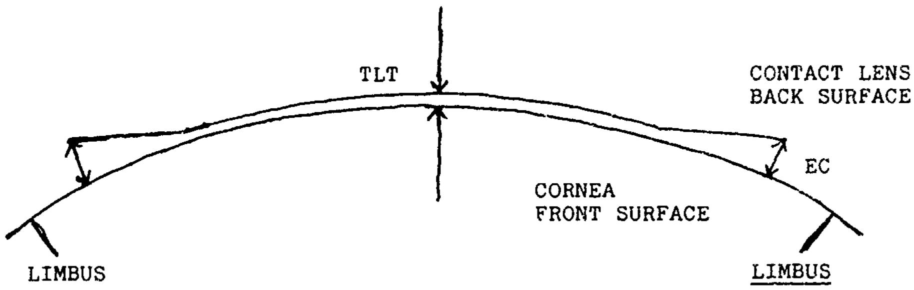


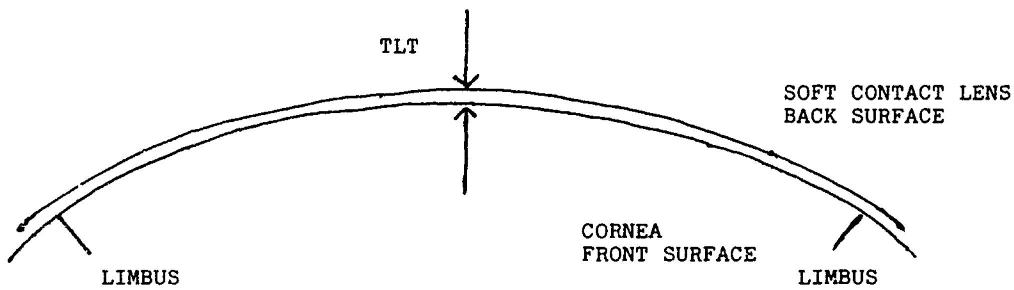
TLT = TEAR LAYER THICKNESS [5]

VALUES CAN RANGE FROM 0.010 TO 0.030 mm

EC = EDGE CLEARANCE

VALUES CAN RANGE FROM 0.060 TO 0.100 mm (Reference 5)

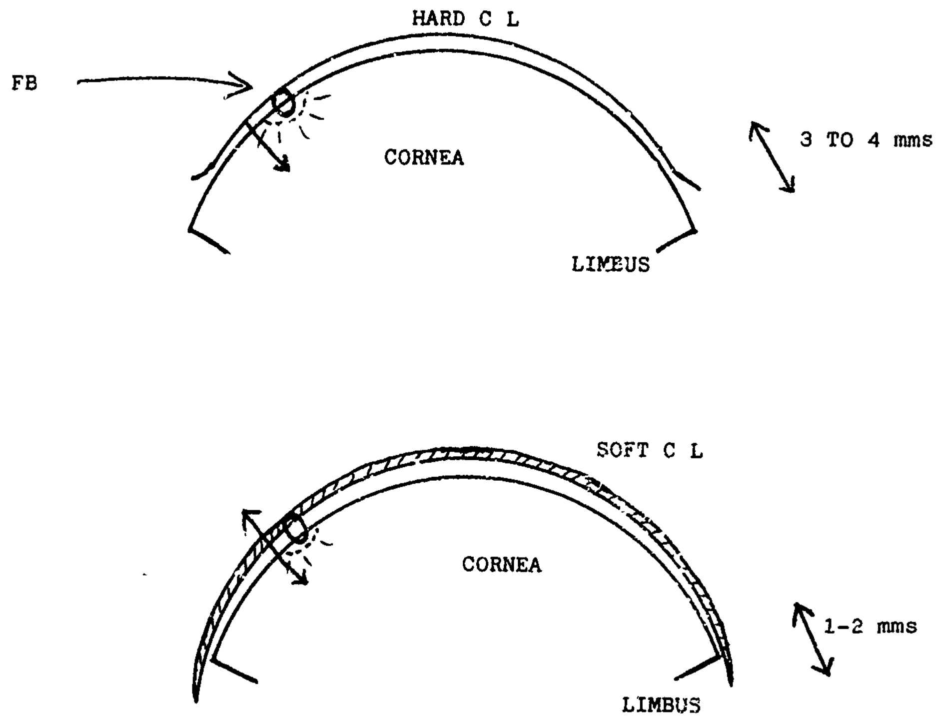
FIGURE 1



TLT = TEAR LAYER THICKNESS

VALUES CAN RANGE FROM 0.005 TO 0.015 mm

FIGURE 2



The rigid hard lens forces the FB into the Soft Cornea. Below the FB impaction is shared between the Soft Cornea and the Soft C L.

FIGURE 3

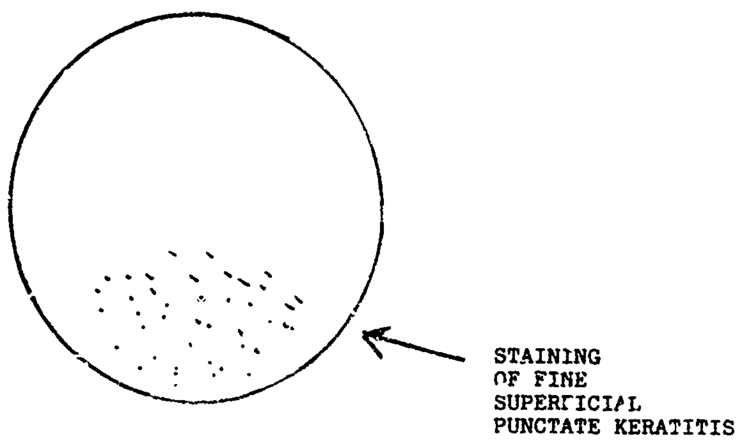


FIGURE 4

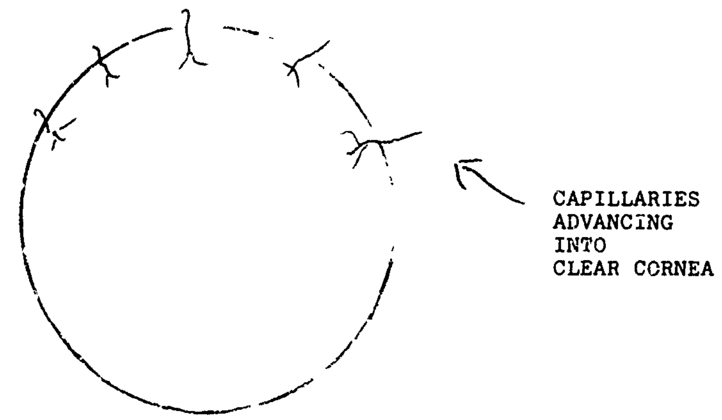


FIGURE 5

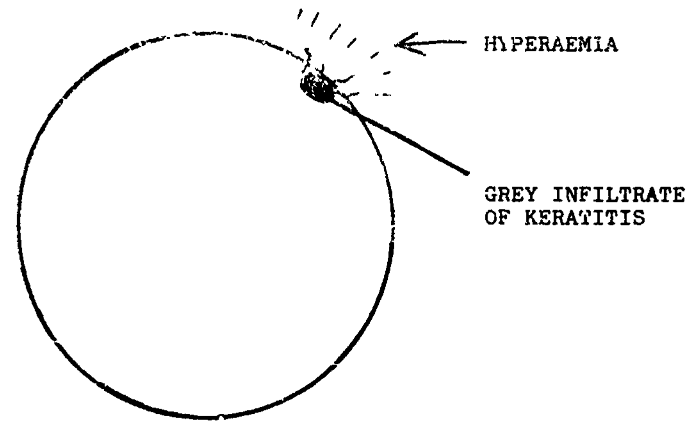


FIGURE 6

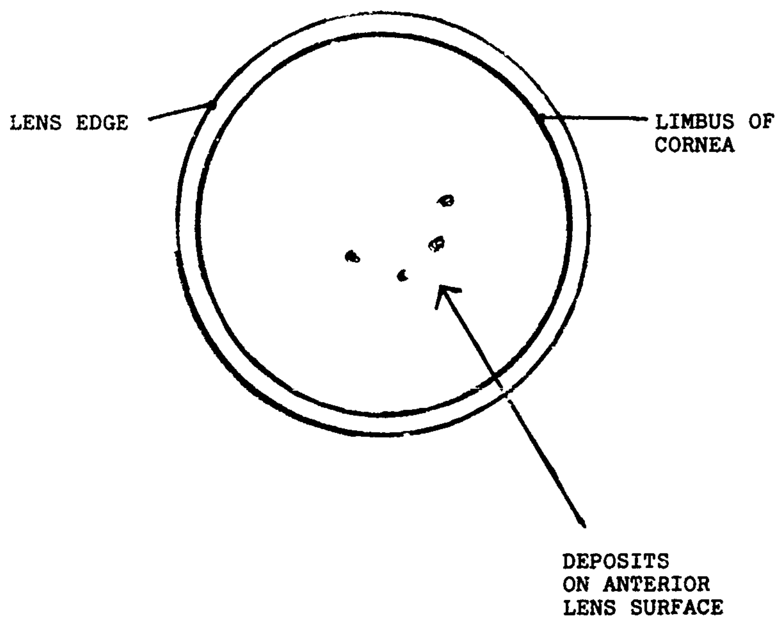


FIGURE 7

Na/K RATIO				SCANLENS 75
		BEFORE	1000	2200
RIGHT EYE	MEDIAN	8.43	9.02	8.48
LEFT EYE	MEDIAN	9.5	9.4	8.79
BOTH	MEDIAN	8.96	9.19	8.64

SIGNIFICANCE TEST		WILCOXON PAIRED T STATISTIC	P
RIGHT EYE	BEFORE - 1000		$P > 0.05$
	BEFORE - 2200		$P > 0.05$
LEFT EYE	BEFORE - 1000		$P > 0.05$
	BEFORE - 2200		$P > 0.05$
BOTH	BEFORE - 1000		$P > 0.05$
	BEFORE - 2200		$P > 0.05$

TABLE 1 Na/K RATION IN TEAR FLUID SAMPLES

READINGS BEFORE LENSES INSERTED

READINGS LENSES BEING WORN AT 1000 Hrs

READINGS LENSES BEING WORN AT 2200 Hrs

396 SAMPLES

SCHIRMER				SCANLENS 75
		BEFORE	1000	2200
RIGHT EYE	MEDIAN	20	22	16.5
LEFT EYE	MEDIAN	19	19	14.5
BOTH	MEDIAN	19.5	21.5	15.0

SIGNIFICANCE TEST		WILCOXON PAIRED T STATISTIC	P
RIGHT EYE	BEFORE - 1000		$\boxed{P < 0.05 \quad > 0.02}$
	BEFORE - 2200		$P > 0.05$
LEFT EYE	BEFORE - 1000		$P > 0.05$
	BEFORE - 2200		$P > 0.05$
BOTH	BEFORE - 1000		$P > 0.05$
	BEFORE - 2200		$P > 0.05$

TABLE 2 SCHIRMER STRIP READINGS OF TEAR PRODUCTION

READINGS BEFORE LENSES INSERTED

READINGS LENSES BEING WORN AT 1000 Hrs

READINGS LENSES BEING WORN AT 2200 Hrs

396 SAMPLES

OSMOLALITY				SCANLENS 75
		BEFORE	1000	2200
RIGHT EYE	MEDIAN	326	342	332
LEFT EYE	MEDIAN	332	353	341
BOTH	MEDIAN	329	347	338

SIGNIFICANCE TEST		WILCOXON PAIRED T STATISTIC	P
RIGHT EYE	BEFORE - 1000		P > 0.05
	BEFORE - 2200		P > 0.05
LEFT EYE	BEFORE - 1000		P > 0.05
	BEFORE - 2200		P > 0.05
BOTH	BEFORE - 1000		P > 0.05
	BEFORE - 2200		P > 0.05

TABLE 3 OSMOLALTIY OF TEAR FLUID

READINGS BEFORE LENSES INSERTED

READINGS LENSES BEING WORN AT 1000 Hrs

READINGS LENSES BEING WORN AT 2200 Hrs

305 SAMPLES

DYNAMIC BEHAVIOUR OF SPHERICAL AND ASPHERICAL CONTACT LENSES EXPOSED TO +Gz-ACCELERATION FORCES

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SUMMARY

A study has been made of the behaviour of two types of hard contact lenses fitted to a young myopic pilot and exposed to +Gz-acceleration forces. We were particularly interested to find out the degree of dislocation of the hard lenses and to detect pathological phenomena of the cornea under increasing +Gz-forces. The two types of the evaluated contact lenses are:
- a conventional spherical polymethylmethacrylate (PMMA) lens
- an aspherical gas-permeable lens (Sil.-O2-Flex)

In the human centrifuge of the National Aerospace Medical Centre at Soesterberg, the testperson was exposed to +Gz-forces increasing from +1 to +9 Gz. In the gondola a videotelecamera was focussed at the head of the testperson during the total testsession. It could be concluded the aspherical gas-permeable contact lenses maintained an optimal centration under all circumstances. The conventional hard contact lenses (PMMA) with a spherical base curve and a smaller diameter showed downward decentration under increasing +Gz-loads from +6 Gz to a peak value of 8,6 Gz. However, the dislocation never caused the contact lens to leave the cornea. The results of this study are discussed in relation to practical consequences for pilots flying high performance aircraft.

INTRODUCTION

Research of the use of hard contact lenses in jet-aircrafts has already been started in the forties. Initially, this research was focussed on studies on scleral lenses. The limited wearing time was considered as an important contraindication for use in the air force (DUGUET a.o., BURKI)
Although the corneal perspex lenses, which were designed in the fifties, realised much more wearing comfort and permitted a longer wearing period, they were not generally accepted as useful for pilots. This opinion had mainly been based on the phenomenon of gas bubble formation behind the lens at high altitude, which would interfere with visual acuity (PERDRIEL). Only incidentally positive case reports were mentioned of hard contact lenses worn by jet pilots (de VRIES, HOOGERHEIDE).
The cautious attitude towards the use of hard contact lenses by fighter-pilots seems to exist also in modern times. This attitude is mainly based on the properties of the small PMMA corneal lenses (FORGIE):
- spectacle blur
- irritation by foreign bodies behind the contact lens and the chance of corneal abrasion
- possible loss of the contact lens during flight.

Some case reports on hard contact lens worn by fighter-pilots seem to confirm these disadvantages (NILSSON, RENGSDORFF).
Since the introduction of the soft lenses, studies were concentrated on the application possibilities of such lenses in the air force. Experiments of TREDICI (personal information) and FORGIE on the behaviour of soft lenses, exposed to +Gz-acceleration with a peak value of +6 Gz showed a downward displacement of the lens , which was in no case great enough to interfere with optical correction.
The recent development of the so called "extended wear" soft lenses, which can be worn for weeks continuously, seems also to increase the possibilities for use by the air force (NILSSON and RENGSDORFF).
However, there is an important disadvantage, introduced by the softlens: it does not give sufficient optical correction in case of corneal astigmatism. The use of toric soft lenses does not offer a good alternative in extreme circumstances, because of the visual instability of this type of lens. In addition, some investigators have reported problems with soft contact lenses, exposed to a low relative humidity in the cockpit (ENG e.a.).
Recent developments in the field of hard contact lenses concerning design as well as material proved to be of great value (ROUWEN e.a.). During the last 2 years we have successfully experimented with the fitting of aspherical Sil-O2-Flex lenses in the Netherlands Army and Air Force.
A request by RNLAF medical authorities to assist in evaluation of a fighter-pilot, wearing contact lenses enabled us to perform a comparitive study on dynamic behaviour of conventional spherical PMMA and aspherical Sil-O2-Flex contact lenses exposed to +Gz-acceleration forces.

TESTPERSON

A 36-year-old myopic Royal Netherlands Air Force (RNLAF) fighter-pilot with 2000 flying-hours in the NF5, was considered for the F-16 conversion. In the past this pilot has received a waiver for flying with contact lenses and had been flying with hard PMMA lenses without problems. RNLAF medical authorities were reluctant to waiver this pilot for flying the F-16 (a "high sustained G" aircraft). It was desired by the RNLAF Aviation Medicine Division that Gz trials in the human centrifuge had to be executed in order to assume that no displacement of the lenses would occur in a high Gz environment to such a degree that vision impairment would result.

Results of opthalmological examination:
Adnexa, media and fundus were normal.
VOD: S-1,00 : 1,25
VOS: S-4,00 = C-0,5 x 120: 1,2
Cornea:

OD:	Ro1: 7.62 m.m.	Excentricity	Mean: 0.7	RS temp: 7.8 m.m.
	Ro2: 7.60 m.m.		Hor : 0.74	RS nas.: 8.3 m.m.
	V.I.D.:		Vert: 0.56	RS inf.: 7.7 m.m.
	Hor : 11.4 m.m.			RS sup.: 8.0 m.m.
	Vert: 10.3 m.m.			
OS:	Ro1: 7.54 m.m.	Excentricity	Mean: 0.88	RS temp: 8.2 m.m.
	Ro2: 7.44 m.m.		Hor : 1.0	RS nas.: 8.4 m.m.
	V.I.D.:		Vert: 0.5	RS inf.: 7.5 m.m.
	Hor : 11.3 m.m.			RS sup.: 8.1 m.m.
	Vert: 10.5 m.m.			

MATERIAL AND METHOD

1. Human centrifuge.
For evaluation the human centrifuge of the National Aerospace Medical Centre has been used. There is a possibility to expose the testperson up to +Gz-acceleration forces of more than + 10 Gz. All simulated profiles are fully computer controlled. Video-tape recording made it possible to study the effects of the acceleration forces on the contact lens. A monitor directly in front of the pilot showed an outside world picture with horizon and fixation cross. Via a computer a simulated target cross can be fed in. By tracking this target the pilot "flies" a pre-set profile.

2. Contact lenses.
a. one pair of conventional PMMA contact lenses.
Each lens was marked with 4 triangular white dots to facilitate determination of lens position.
The posterior surface of this non-gaspermeable lens has been constructed with the aid of 3 lath cut curves: the base curve (BCR) and 2 peripheral curves.
The peripheral flattening is necessary because the cornea possesses a central spherical area of about 4 mm and outside a gradually flattening transition (Excentricity E), more or less abruptly ended in the sclera.
Problems arise from the fact the flattening of the contact lens often has been standardized despite a great individual variation of the cornea curvature (cf. difference of excentricity ODS: OD: 0.7; OS: 0.88). In addition, at a large lensdiameter the discongruention between peripheral corneal curve and contact lens will be more significant. In fittings like these the consequences are:
less wear comfort, bad circulation of tears behind contact lens, which causes O2-deficiency of the corneal epithelium.
Specifications of the lenses:

OD: BCR 7.70 mm	OS: BCR 7.60 mm
lensdiameter 9.0 mm	lensdiameter 9.2 mm
spherical lenspower -1.00 D	spherical lenspower -2.25 mm D
central thickness 0.22 mm	central thickness 0.2 mm
visual acuity 1.25	visual acuity 0.9

b. two pairs of aspherical Sil-O2-Flex contact lenses.
One pair had been marked with 4 triangular white dots.
This siloxanyl co-polymer with high O2-permeability has a base curvature with an elliptic curve from centre to lensedge. The elliptic design approaches the anatomical curvatures of the cornea.
The consequences of the aspherical design are:
- a parallel tear-lens results in a better circulation and O2 delivery. Besides there will be a maximum of cohesive power, which aids centration of the lens
- absence of pressure areas will induce less spectacle blur
- absence of peripheral curves results in a large effective optical zone (nearly the total lensdiameter). So also in case of lens movements the possibility of lens-edge flare is minimal
- the elliptic base curve in combination with the high degree of O2- permeability permits fitting of a large lensdiameter, which results in more stability of the lens.

Specifications of the lenses:

OD: BCR 7.60 mm	OS: BCR 7.65 mm
lensdiameter 9.8 mm	lensdiameter 9.8 mm
spherical lenspower -1.00 D	spherical lenspower -3.5 D
Excentricity 0.6 mm	excentricity 0.7 mm
central thickness 0.21 mm	central thickness 0.15 mm
visual acuity 1.25	visual acuity 1.25

3. Protocol.

4 flight profiles were made with the aspherical contact lenses, while 2 profiles were performed with the conventional PMMA lenses. The recorded, magnified videopictures were observed afterwards. The horizontal and vertical deviations were measured in millimeters, using the bounderies of the iris as a reference. The measurements were corrected to the real value. The position of both lenses at +1G was used as a zero value for subsequent measurements. The measuring error of this method was calculated as 0.2 mm. As control the behaviour of both contact lens types were recorded at + 1Gz.

- profile 1 and 4 were gradual onset-profiles with + 1Gz increase per 10 seconds to a Gz-level at which the pilot experienced peripheral light loss. Both profiles were computer controlled. Profile 1 was carried out with the aspherical contact lenses and profile 4 with the conventional type. A +Gz value of 8.6 Gz was reached during both profiles.
- profile 2 was a pilot controlled one with a peak of + 6 Gz for 30 seconds. The aspherical contact lenses were used. Exposed to + 6 Gz loading, extreme horizontal gaze movements were made for a period of 30 seconds. The horizontal and vertical decentration was measured respectively in extreme ab- and adduction.
- profile 3 and 5 were similar except that the computer controlled the steering. During profile 3 the aspherical contact lenses were worn and during profile 5 the conventional ones. The maximum + Gz level was reached at + 6 Gz. As in profile 2 horizontal gaze movements were made at a + 6 Gz level during one minute.
- During the last profile a pilot controlled Simulated Air Combat manoeuvring mission was flown with high onset rate of +3,5 Gz per second to +8.5 and +9 Gz-peaks. The aspherical unmarked contact lenses were worn.

Before and after each profile visual acuity, refraction and keratometry were determined. Splitlamp examination was performed with help of installation of fluorescein. The fluorescein fitting pattern of the lens was photographed.

RESULTS

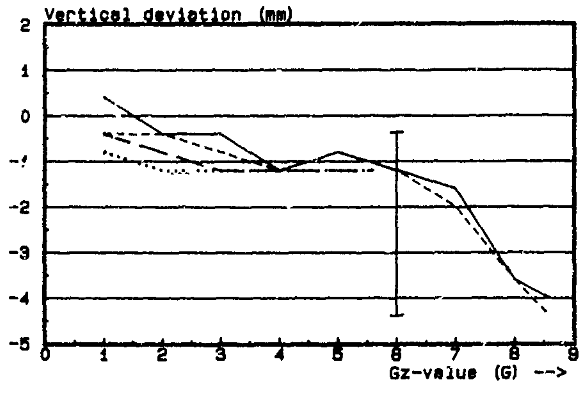
With increasing + Gz-forces a ptosis was observed. This phenomenon was more significant in the left eye. Sometimes the left eye was nearly closed and the testperson seemed to use only his right eye as reference. This caused some measurement difficulties by the observers.

Examination of the conventional PMMA lenses:

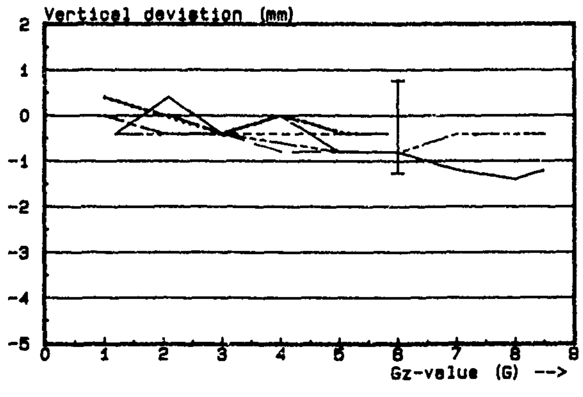
- In profile 4 it was observed that the lenses were displaced downward starting at a level of +6 Gz and moving down with increasing + Gz until a maximum displacement of 4.5 mm at the peak value of 8.6 + Gz (graph. 1). A significant relation between horizontal deviation and increasing + Gz-forces was not found. In general the deviations of the lenses were instable, jerky and strongly influenced by blinking action and facial tensing.
- During peak + Gz-loading profile 5 showed downward movements with a maximum of 4.5 mm at extreme abduction and adduction (Graph 1). It was further observed that the lens of the right eye nearly slipped from the cornea to lateral at a gaze movement to the right. Through blinking action the lens returned to the cornea.

Examination of the aspherical Sil-02-Flex contact lenses:

- During profile 1,2 ans 3 lenses maintained a good centration under all circumstances. There was not a significant relation between displacements of the lenses and increasing +Gz, right up to the extreme horizontal gaze movements (Graph. 2.). The movements of the lenses were hardly influenced by blinking and facial tensing.



Graph. 1.



Graph. 2.

Graph. 1.
BEHAVIOUR OF PMMA LENSES EXPOSED TO +Gz.
Profile 4: a significant downward movement of the lenses ODS, starting with +6 Gz and increasing until a maximum of 4.5 mm at the peak of +8.6 Gz.
Profile 5: vertical displacements of the lenses ODS without a significant relation to increasing +Gz up to +6 Gz.
Downward displacements of the lenses, varying from 1/4 mm until 4.5 mm at extreme adduction and abduction at a level of +6 Gz (ODS I)

Graph.2.
BEHAVIOUR OF SIL-O2-FLEX CONTACT LENSES EXPOSED TO +Gz.
Vertical displacements of the contact lenses ODS: no significant relation to increasing +Gz up to +8.6 Gz (profile 1). up to +6.0 Gz (profile 2 and 3). Also under +Gz-loading of +6.0 Gz the vertical deviations are within the normal range at extreme abduction and adduction (profile 2 and 3: ODS I)

DISCUSSION

1. Although stringent vision criteria exist for the candidate pilot it is very well possible that a minor myopia will develop after some years. In that case the aircrewmember has to be waivered for flying with correction spectacles. Most aircrew-spectacle, although correcting the visual acuity do possess some disadvantages:
   a. the spectacle-frame may interfere with operational or personal-safety equipment (i.e. light weight visor, oxygen mask, NBC protective mask, nuclear flash goggles or night vision equipment).
   b. some spectacle-frames displace during high +Gz-loads. Observations during centrifuge training show a specific type frame to slip up or down at +Gz- loads over +5 Gz.
   c. During night- and instrument flying the reflection of the many optic systems in a modern fighter-aircraft may create a desorientation hazard when the pilot is wearing glasses, even when these glasses are provided with an anti-glare coating
   d. Changing temperatures and airflow directions in the cockpit may blur the glasses due to condensation of water vapour.

   Most of the above-mentioned disadvantages can be overcome by the use of well fitted contact lenses. The chance however of decentration or inadvertent loss must be minimal.
2. This study shows that there is no significant decentration of hard lenses during increasing + Gz-forces up to about +5 to +6 Gz. This corresponds with the experience of our testperson, who did not have any visual problem with his hard lenses flying the NF5-aircraft. Also Draeger, who tested the behaviour of hard lenses in the human centrifuge up to a peak of +3 Gz, came to the same conclusion.
   However, exposed to increasing + Gz-values above +6 Gz conventional PMMA lenses were decentrating in such a degree that vision became jeopardized. During horizontal gaze movements there was a tendency of total lens slippage. Even if the lens is not lost during a +Gz-induced decentration, the small optical zone of the PMMA lens may easily caused flare. Particularly during night flights, when the pupils are wide, there is a higher risk of glare problems. In this experiment the aspherical lens proved to have great advantages. Its larger diameter and optical zone takes care of a better centration and a unobstructed vision. It reduces also the possibility of glare. This subpalpebrally fitted lens, with a small edge lift, reduces the risk of loss and foreign bodies behind the lens.

CONCLUSIONS

1. Conventional PMMA contact lenses do not create problems when exposed to +Gz forces, not exceeding values of +5 Gz.

2. The stability of aspherical Sil-02-Flex contact lenses proved to be far superior to the conventional PMMA lenses under Gz-loads above +5 Gz.

3. The difference between the behaviour of contact lenses may be manifest under extreme circumstances. Therefore all jet-fighter pilots considered for a waiver for flying with hard contact lenses should only be waivered for the use of the aspherical lens type after individual evalutation in the human centrifuge.

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Effects of Broad-banded Eye Protection on Dark Adaptation

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SUMMARY

Modern combat scenarios require soldiers to perform military tasks under night time conditions. While image enhancement devices are vital to such military performance, unimpaired human night vision retinal mechanisms are essential for performance success. Protection of the human biological sensor is of utmost importance. In this investigation we have reexamined earlier findings indicating that sunglasses could prevent deleterious effects of bright light on dark adaptation. We found that the use of broad-band attenuating spectacles could improve absolute visual thresholds but they had minimal effect on central retinal mechanisms. Dark adaptation functions measured with long-wavelength light showed no significant sunglass effect; whereas, such functions measured with intermediate spectral light decreased in final visual thresholds. These differential effects were obtained under environmental light conditions insufficient to produce an elevation in final visual thresholds for control group subjects not provided with sunglasses. The results of this study strongly support previous arguments for providing standard visible and near ultraviolet protection to personnel required to perform military tasks under extremely bright environmental light.

Many current field exercises conducted within the Army involve extensive night maneuvers and require optimal human night vision performance. With the availability of modern night vision devices, dependence upon unaided human night vision has been minimized. Yet the usefulness of unaided night vision must not be overlooked, because modern night vision devices are available only in limited quantities, they may produce visual fatigue after short periods of time and may have restricted fields of view. In this experiment we investigated the potential for augmenting natural human night vision function as an alternative to its artificial augmentation.

Exposure to bright daylight conditions occasionally has been associated with a decreased rate of dark adaptation (1,2). Furthermore, chronic daily exposure to bright environmental light has been associated with changes in gross retinal morphology and visual function (3,4). These investigations (3,4) in animal subjects have shown that such levels can produce significant retinal degeneration as well as permanent elevation in rod absolute threshold.

An early study (2) on human dark adaptation indicated that prolonged exposure to bright environmental light produced a delay in the rate of adaptation, as well as a reduction in final absolute sensitivity. Also reported in this study was the result that the use of sunglasses under such lighting conditions could prevent these changes.

Although bright light environments can decrease final dark- adapted visual sensitivity, little is known about the differential effects on the types of photoreceptor systems. Neither is it known if sunglasses change final visual threshold levels only under excessively bright light levels. Such additional information can help elucidate the nature of the retinal mechanisms and thereby increase our ability to understand how to augment unaided night visual function. The present experiment was undertaken to answer such questions.

METHOD

A light emitting diode (LED) dark adaptometer (5,6) was used in this experiment. A composite illustration of this device is presented in Figure 1. Red and green LED sources are mounted inside a plexiglass hemisphere. Measurements of visual threshold (visual sensitivity is the reciprocal of visual threshold) following a standard period of light adaptation were made with a tracking technique (5). Volunteers were required to press and hold a response button when either a red or green light was seen by them, and release the button when the light was no longer visible. The 36-inch hemisphere, fitted with a chin support and headrest, and indirectly illuminated with conventional tungsten lamps, provided a constant uniform light adaptation source of 110 candela/m^2. Threshold measurement were alternately determined for both red and green LED sources during the course of dark adaptation.

In these experiments all threshold measurements were made at 16 degrees from fixation for the red (E) and green (C) LED sources. Both vertical and horizontal LED sources were illuminated simultaneously for each source. The spectral distributions

of the two kinds of sunglasses used in this experiment are shown in Figure 2a,b. The luminance transmittance of the Olo sunglasses using the CIE C source equalled 1.3%, while that for the Gargoyle sunglass equalled 18%. For both of these filters, transmission in the near ultraviolet spectrum was no more than 5%.

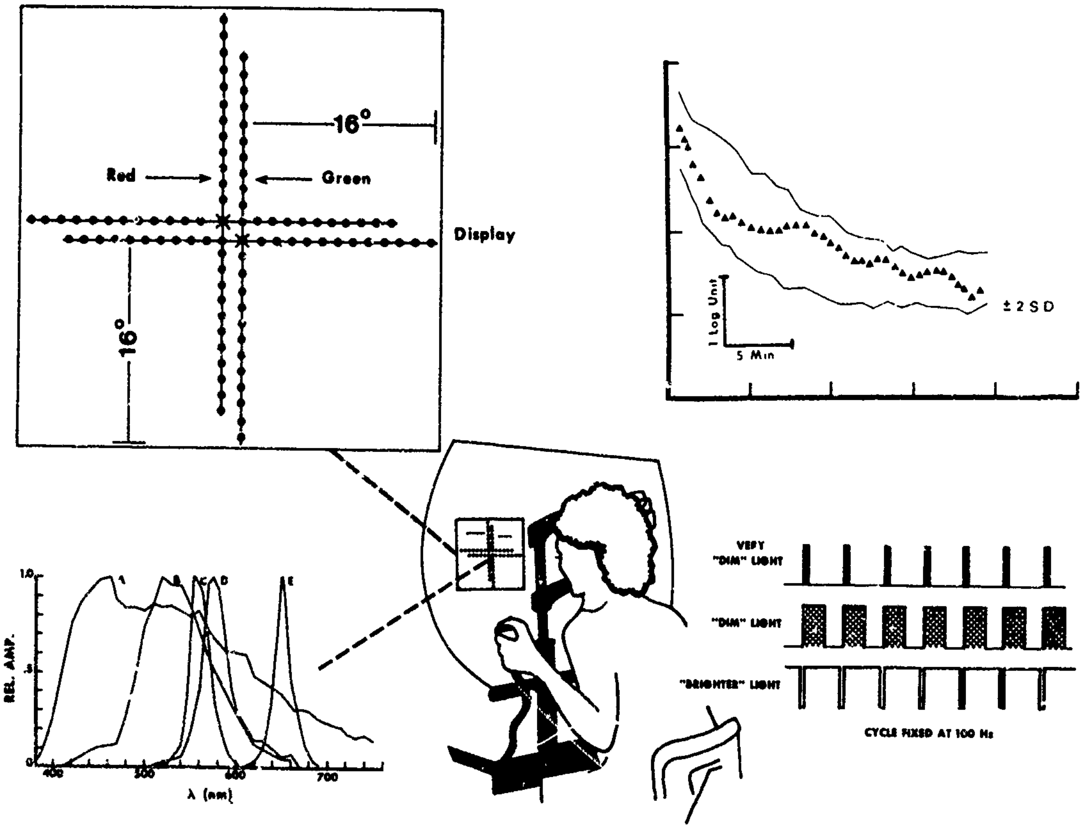


Figure 1. A schematic illustration of the LED dark adaptometer. In the upper right, a sample dark adaptation function from one individual is shown. The upper and lower solid lines represent two standard deviations about the mean function. The duty cycle or pulse width modulation for a dim light (late dark adaptation) is shown in the lower right insert. Threshold pulse width decreases as dark adaptation increases. The relative spectral transmission curves of the LED sources available to this apparatus are shown in the lower left corner. For this experiment only the green (C) and red (E) diodes were used.

Experimental and control group subjects were military personnel on maneuvers in a semi-arid environment at Fort Hunter Liggett Military Reservation in California. All subjects were in their mid-twenties. Both experimental (n=15) and control (n=15) groups received a standard dark adaptation test, which consisted of a 2-minute light adaptation period within the hemisphere followed by visual threshold measurements made for both the red and green LED sources. Visual threshold measurements were made over a 20-minute dark adaptation period. The experimental group was given one of the two kinds of sunglasses described in Figure 2 and asked to use these filters, when outdoors, as much as they possibly could. No filters were given control group subjects, who were engaged in similar activities under nearly identical environmental conditions. Reported average usage of sunglasses over the four days between before and after measurements of dark adaptation equalled about 20 hours for each subject.

RESULTS

Dark adaptation functions for spectral test stimuli are shown for two subjects in Figure 3a,b. While the subjects show large individual variation in the effects, their functions demonstrate the trends that were found in all of the subjects. Both show that throughout the dark adaptation measurement period, post-exposure thresholds for the green LED source were always lower than those obtained for the preexposure period. Measurements of sensitivity for the red LED show much smaller differences as well as crossovers during the 20-minute dark adaptation period.

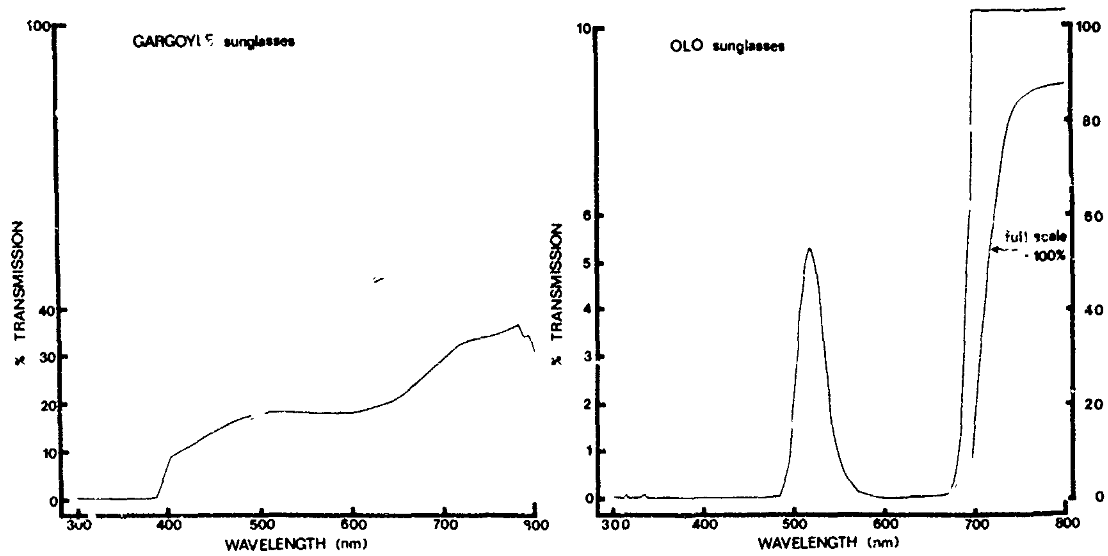


Figure 2 a,b. Spectral transmittance of Gargoyle and OLO sunglasses. The luminance transmission of these filters using the CIE C source was 18% and 1.3%, respectively.

Differences in either the spectral transmission of these filters or in the amount of time filters were actually worn by these subjects may account for the large individual differences. However, the average for the 15 subjects wearing sunglasses supports the observations gained from the two subjects (Figure 4). Average post-exposure measurements of sensitivity for the green LED light source are approximately a quarter of a log unit more sensitive than average preexposure measurements over most of the dark adaptation period, but are minimal for the red LED.

Comparable dark adaptation measurements made with the 15 control subjects show no differences between pre- and post-exposure for either the green or red LED test stimuli. The data from these two curves were examined with a 4-way ANOVA, which revealed a statistically significant 4-way interaction ($P<.05$) for filter, LED color, time, and pre- and post-exposure. Statistical analysis was conducted for the first and last 5-minute blocks in the dark adaptation period. To further define the significant contributing factors to this 4-way interaction, we examined the factors of LED color, time, and pre- vs post exposure for sunglass group vs control group. The results of the three-way analysis for both of these groups are shown in Tables 1 and 2. The major differences in these separate ANOVAs lay in the significance of the interactions between pre- and post-exposure and color. The sunglass group had significant interactions between color and time and between pre-/post exposure and time.

Multiple comparisons with paired t - tests were done for the sunglass group only since pre-/post-exposure did not show up as a significant factor in any of the interactions tested for the control group. The post measurements were statistically significant ($p<.05$) for the green LED over the last 5 minutes of dark adaptation but were not statistically significant for the first 5 minutes of dark adaptation.

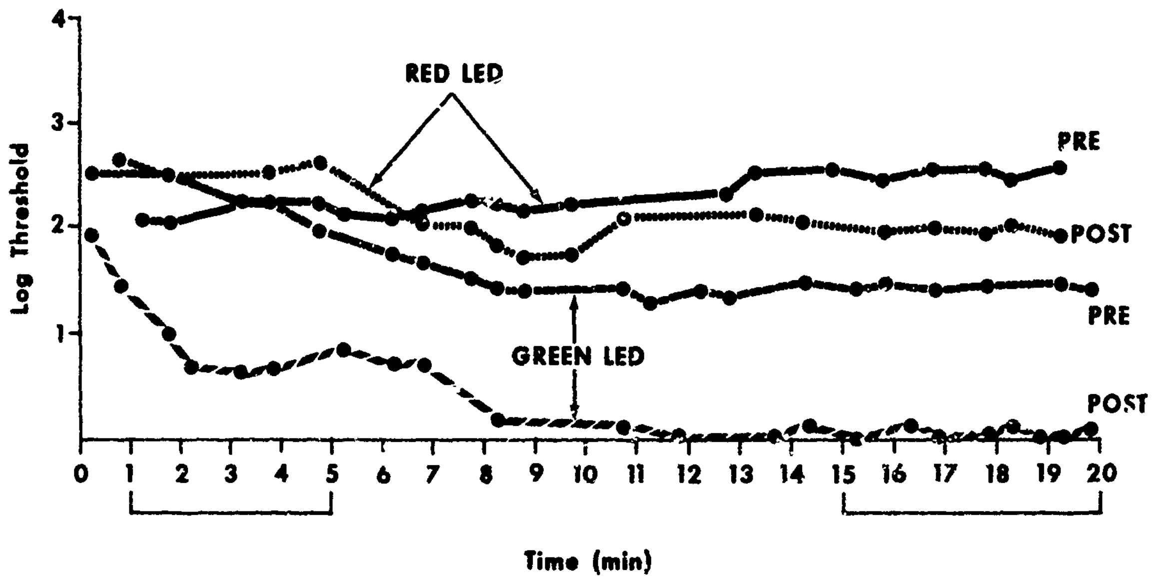
DISCUSSION

The results of this experiment support previous findings on the effects of sunglass usage on final dark adapted visual sensitivity (2); i.e. an increase in visual sensitivity was obtained for peripheral retinal measurements. However, this effect was spectrally selective, occurring for the intermediate but not for the long wavelength test light source. This finding suggests that the long wavelength cone receptor system is insensitive while either the rods or possibly the intermediate cone system are sensitive to such light filtration. Furthermore, the increase in final sensitivity was obtained in the absence of an elevation in visual sensitivity produced by unfiltered environmental light, as evidenced by the control groups pre- and post-exposure data.

Augmentation of a natural photic protective mechanism is one explanation of our findings. One difference between paramacular and macular receptors is that light for the latter group of receptors is filtered by macular pigment, which absorbs short-wavelength visible light. Maximum absorption of the macular pigment is 460 nm. Estimates of the optical densities of this pigment range from 0.3 to 0.85 (7,8). As short-wavelength light in the blue region of the spectrum has been postulated (9,10) to represent the most hazardous portion of the visible spectrum, the macular spectral absorption characteristics seem to provide a natural protective filter from intense levels of short-wavelength visible light. Sunglasses may afford a degree of spectral protection to the paramacular receptors.

The two filters used in this experiment were of different absorption

OLO



GARGOYLES

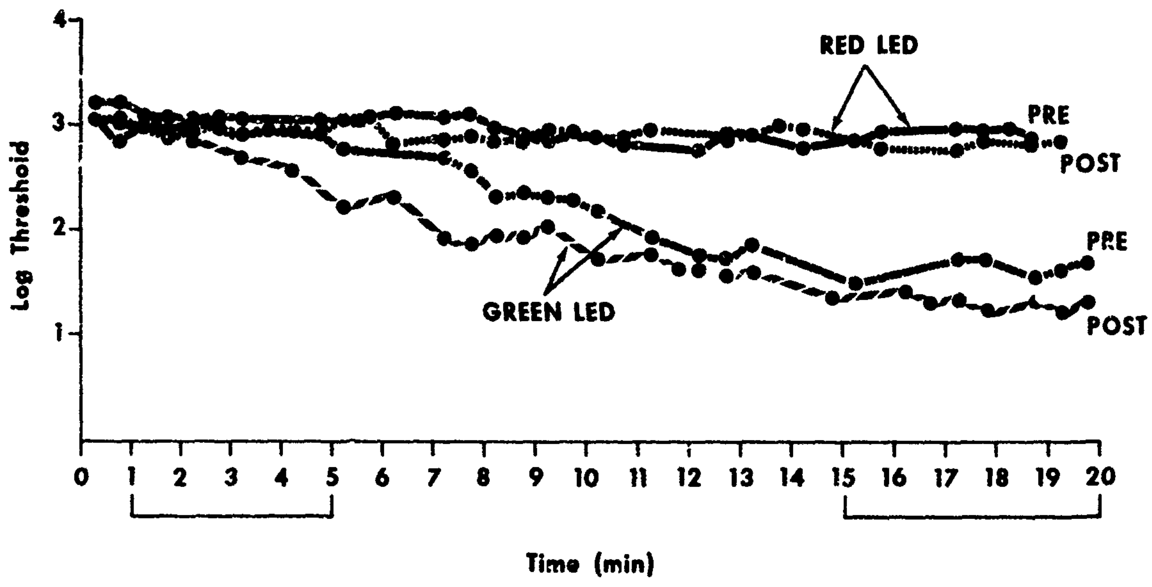
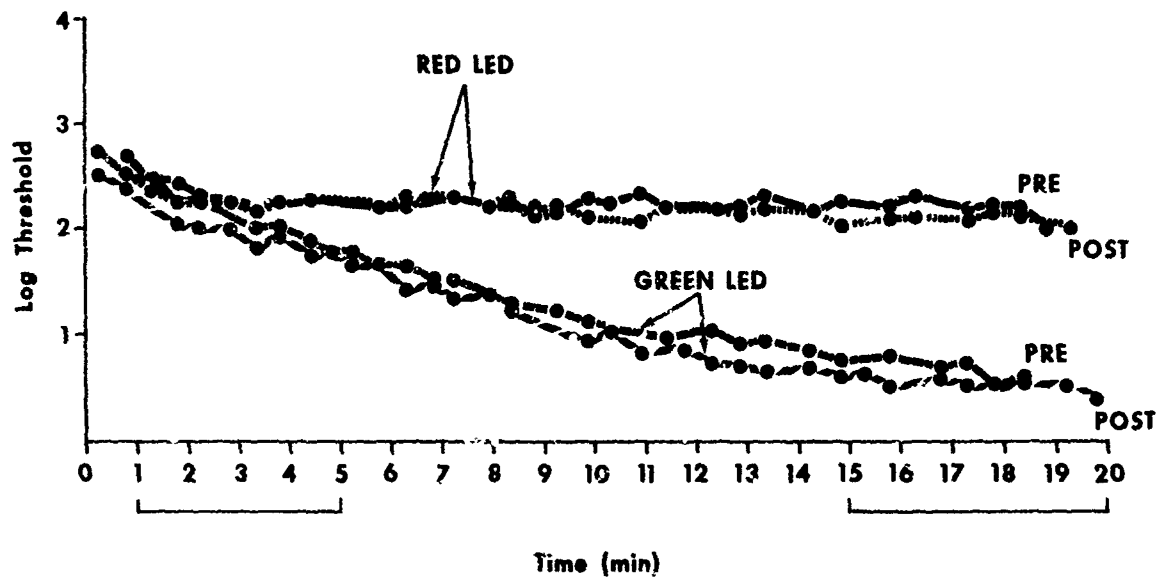


Figure 3a,b. Two subjects showing the pre- and post-exposure dark adaptation measurements. One subject used the OLO filter and the other used the Gargoyle filter. Both subjects show the same relative effects for pre and post spectral dark adaptation measurements, although absolute differences were greater for the subject wearing the OLO filter as compared with the one wearing the Gargoyle filter.

SUNGLASS GP - N=15



CONTROL GP - N=15

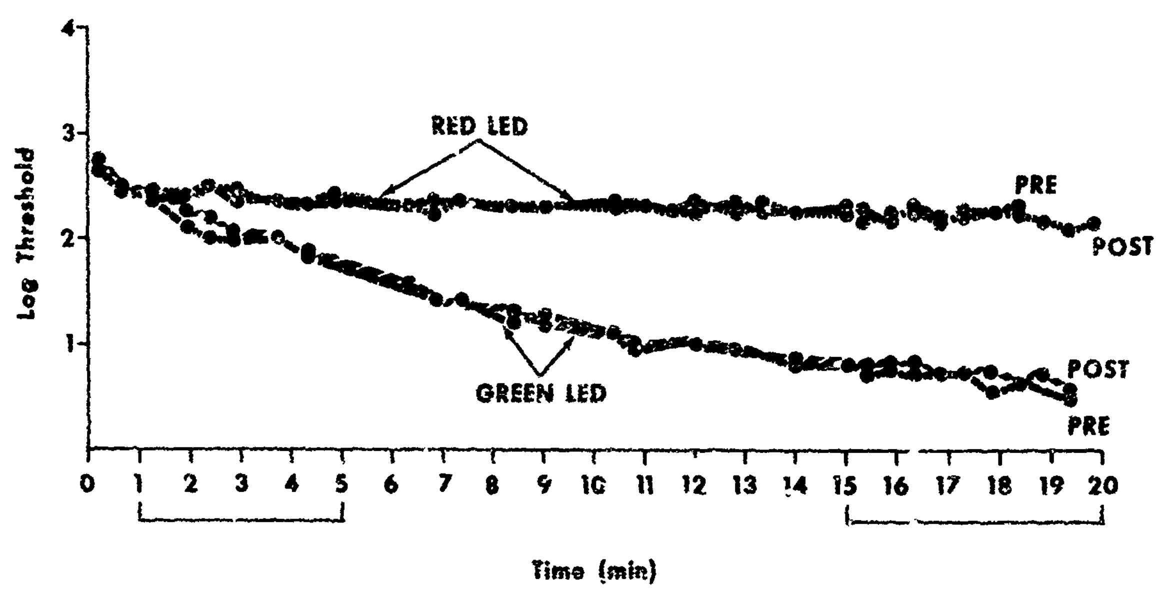


Figure 4a,b. Pre and post average dark adaptation functions for sunglass group(a) and control group(b).

TABLE 1

SUMMARY OF ANALYSIS OF VARIANCE
FOR EXPERIMENTAL GROUP*

SOURCE	DEGREES OF FREEDOM	MEAN SQUARE	F	PROBABILITY†
MEAN	1	542.17254	1865.2	ns
ERROR	14	.29061		
PRE/POST	1	.19764	.30	ns
ERROR	14	.21954		
COLOR	1	18.07304	1127.94	.0000
ERROR	14	.01602		
PRE/POST X COLOR	1	.02002	.66	ns
ERROR	14	.03016		
TIME	1	30.77494	414.27	.0000
ERROR	14			
PRE/POST X TIME	1	.34454	6.97	.0194
ERROR	14	.04943		
COLOR X TIME	1	21.14280	1202.25	.0000
ERROR	14	.01759		
PRE/POST X COLOR X TIME	1	.28714	11.76	.0041
ERROR	14	.02442		

* THE ANALYSIS WAS PERFORMED USING BIOMEDICAL COMPUTER PROGRAMS BMDP2V.

† THE P = .05 LEVEL WAS USED FOR DETERMINING STATISTICAL SIGNIFICANCE.

TABLE 2

SUMMARY OF ANALYSIS OF VARIANCE
FOR CONTROL GROUP*

SOURCE	DEGREES OF FREEDOM	MEAN SQUARE	F	PROBABILITY†
MEAN	1	596.30209	1760.05	ns
ERROR	14	.33880		
PRE/POST	1	.01541	.22	ns
ERROR	14	.07160		
COLOR	1	11.32216	121.74	.0000
ERROR	14	.09301		
PRE/POST X COLOR	1	.01281	.39	ns
ERROR	14	.03248		
TIME	1	19.28009	410.05	.0000
ERROR	14	.04702		
PRE/POST X TIME	1	.00588	.19	ns
ERROR	14	.03081		
COLOR X TIME	1	12.81840	834.50	.0000
ERROR	14	.01536		
PRE/POST X COLOR X TIME	1	.01825	.79	ns
ERROR	14	.02021		

* THE ANALYSIS WAS PERFORMED USING BIOMEDICAL COMPUTER PROGRAMS BMDP2V.

† THE P = .05 LEVEL WAS USED FOR DETERMINING STATISTICAL SIGNIFICANCE.

characteristics in the visible spectrum, but nevertheless had similar effects on absolute visual thresholds. This lack of spectral specificity may reflect experimental conditions beyond our control or may be an indication of the importance of the high near ultraviolet absorption common to both of these filters. In the past (11,12,13) considerable discussion had been given to the relative contributions of this portion of the spectrum to elevations in final visual thresholds More recent animal investigations (9,10) have suggested that both the visible and near ultraviolet spectrum may mediate separate photochemical toxicity mechanisms.

While augmentation of the natural protection afforded by the macular pigment is reasonable at levels of environmental light where exposure does produce an observable decrement in sensitivity, no such decrement was obtained in this study, as evidenced by the control group pre- and post-exposure measurements of dark adaptation. The ability to produce an increase in sensitivity in the present study may, therefore, involve other retinal mechanisms in addition to that of natural filter augmentation. Such mechanisms could be more directly involved with the normal regulation of night visual function rather than with its lability to light exposure, at least for environmental light levels that do not elevate or delay final dark adapted visual thresholds.

One such mechanism would involve interference with normal rod-cone interaction processes. During the normal course of dark adaptation, cone activity initially produces the strongest neural response. This early cone activity is able to neurally mask rod activity. As dark adaptation proceeds, the neural output of the rod system increases while that of the cone systems decrease. Measures of spectral sensitivity obtained during the course of dark adaptation reflect these dynamics. The shape of the spectral sensitivity function during the intermediate temporal course of dark adaptation neither fully matches the photopic or the scotopic function (5). The uniform filtration afforded by sunglasses to both the rod and cone receptor systems would alter the balance of rod/cone inhibitory influences and selectively favor peripheral rods, since rods are the most numerous receptor element and, therefore, the receptor system having the greatest neural output.

Minor changes in peripheral retinal receptor orientation may be induced by attenuated retinal irradiance. Normally, primate peripheral retinal rods are oriented toward the pupillary aperture (14), giving a maximally efficient response to light oriented normal to the pupil. Recent investigations (15,16) have demonstrated that retinal receptor efficiency measurements can be altered by grossly attenuated light input over several hours or alteration in the location of the pupil. Other investigations (17,18,19) have demonstrated the presence of striated tissue both in the photoreceptor itself as well as both proximal and distal to the photoreceptor outer segment. Under normal, non-toxic light conditions it is possible that a receptor alignment mechanism may function, capable of fine tuning its orientation for maximal processing efficiency of light input. Under brighter light conditions, such a mechanism may serve to protect the photoreceptor system by slightly disorienting the photoreceptor, causing a reduction in visual efficiency while affording a degree of protection to the photoreceptor absorption apparatus. Such an explanation could also accommodate neural inhibitory processes as well as receptor alignment mechanisms, as a change in receptor orientation, affecting receptor efficiency would also affect the lateral neural inhibitory activity of one receptor on another receptor system.

The present investigation supports previous studies, and suggests the presence of an active retinal receptor alignment mechanism capable of attenuating over a wide range of environmental light levels. Under environmental light levels that do not pose a hazard, sunglasses may serve to maximize normal visual efficiency by optimizing retinal receptor alignment to the pupillary aperture. For light levels that do pose a potential hazard (1,2), retinal receptor alignment processes may serve to "detune" fine receptor orientation to the pupillary aperture, thereby, decreasing visual efficiency, but also affording a degree of protection to the receptor light absorption mechanism itself. Such mechanisms may be required to a lesser degree by macular receptor systems, as the macular pigment serves as a static protective absorption system, or may exist for macular receptors but require more specialized visual inquiry to elucidate their presence.

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DISCUSSION
Papers 14—17

17. Dr H Zwick - USA - Broadbanded Eye Protection.
14. Dr Draeger - Germany - New Glasses for Presbyopic Pilots.
15. Gp Capt Cloherty - UK - Contact Lenses for Pilots and Aircrew in the Services.
16. Dr Punt - Netherlands - Dynamic Behaviour of Spherical and Aspherical Contact Lenses.

Brennan UK: I do not understand how long it took for their dark adaptation to return to normal values when they were no longer exposed to long periods on a Californian beach.

Zwick US: Well first of all we did not use a Californian beach, and I think you are confusing the studies in the 1940s with Naval personnel on beaches in Southern Carolina. Those people were exposed to maybe 6 hrs a day. In our experiment we used Army personnel assigned to Fort Hunter Liggett for a period of about a month. We had them for a total of about 6 days. Firstly we made our test and then we sent them back into the field, they were asked to wear sunglasses, if they were in the sunglass group. They worked under fairly normal skies. We may have had some cloudy days but they were not bright and they were not the same conditions as occurred forty years ago in those other experiments. We did not find a light effect in the control group, in other words there was no effect for the group that did not wear sunglasses. There was no increase in sensitivity, nor was there a decrease in sensitivity. We did not see any effect. We saw the effect only for the group that wore the sunglasses and that was an increase in sensitivity.

Brennan UK: The group that did not wear the sunglasses and that had the effect with the green LEDs, did you then put them into sunglasses for a period and see how long it took for them to return to normal values?

Zwick US: No.

Brennan UK: Do you think it would be a good idea to try with blue LEDs?

Zwick US: The effect is very similar to green LEDs.

Brennan UK: You did not find any significant difference?

Zwick US: We did not find much difference at all. The blue LED we used peaks at about 490nm so it is a mixture of blue-green. It is more towards the longer side of blue. It would be nice if we had a blue LED at 440nm but we do not have that.

Hickman US: Do you feel that whatever visual problems are imposed by a 6 or 7 mm displacement of a contact lens occurring over 6 or 7 seconds at 1G per second onset represents the same problem as a 6 or 7 mm displacement which occurs in 1 second in an aircraft with a high rate of G onset. Are the visual problems the same?

Punt NE: I would think that a displacement of a lens during a long period is indeed much more of a problem than during 1 second. Where there is not total slippage it does not matter with an aspherical lens because the total lens diameter is also the optical area, only, when there is a total slippage of an aspherical lens will there be a problem. To have slippage of a PMMA lens will cause more problems such as flare than the aspherical lens.

Hickman US: I would be interested to hear what Dr Cloherty has to say about the problem of rapid G onset.

Cloherty UK: It has been our experience that the hard lens does move in excess of the high water content lens at +5Gz. Our subject was an experienced centrifuge operator. We would not consider a hard lens for aviators.

Hickman US: It would be helpful to hear from the last two gentlemen a brief statement on what are the indications for contact lenses. Whilst the usage may be increasing is it really needed? Under what circumstances will they out-perform a set of properly fitted spectacles?

Punt NE: Well I think that when there is an astigmatic problem then you have to look for the optimal solution to it and I think aspherical contact lenses with a high degree of gas permeability are the optimal solution to the problem. I think that in the last 10 to 20 years hard lenses have had a bad image because we are talking about the PMMA lens with a small optical area and that is the reason that experiments with soft lenses have now been done by Forgie, Tredici and Brennan. These experiments are very good but I think when there is a cylinder you should try toric lenses. Soft toric lenses are not the solution because of their instability. I cannot recommend them.

Brennan UK: My opinion would be that the time to fit contact lenses in preference to spectacles is when you are forced to deal with equipment of limited eye relief, that would be the primary purpose. Perhaps it would be better to devise optical equipment with a larger eye relief so that the necessity does not arise.

Cloherty UK: We issued our 40 volunteers with a questionnaire. The last question asked was "Would you feel confident using your soft contact lenses?" Every volunteer with one exception, said "Yes". The exception was a doctor who said he was not sure. All the aircrew said they would be quite happy to fly with the soft contact lenses. We do not fit them as a routine because there are other considerations, such as the possibility of any noxious gas or fluid that is water soluble entering the soft lenses. We

are continuing the trial so that we can observe these people and keep the topic under consideration. We have 2 pilots who are aphakic, they require contact lenses to keep them flying and operational, so that is an indication if you wish.

Draeger GE: I would like to refer to Dr Hickman's question about the indications for fitting contact lenses. There is a very simple optical reason that Dr Punt has already mentioned. Vision is markedly improved compared with using spectacles and this applies particularly to astigmatic cases. The second reason is that the mechanical effect of a G load on a contact lens is much less than that for spectacles. Did you ever try to use -4D spectacle lenses and apply a rapid 9G acceleration? The spectacles slip down your nose and perhaps fall off the head and it is very confusing, much more so than when wearing contact lenses. The contact lens wearer is better placed. We are really sure about the superiority of contact lenses under a high G load compared to spectacles.

Brennan UK: It might be better if we did not have to have aircrew who were wearing -4D in the first place.

Biggelaar NE: I would like to answer Dr Hickman's question about the spectacle frames that slip away. We have seen many cases, at least 10, from the population of some 200 aircrew that underwent centrifuge training at the Soesterberg Institute. Most of them were wearing American type frames and it seems that the G value of +5 is critical. Because, beyond that G value one sees the spectacle frames slip or fall off completely. The best frame I have seen so far is an American frame which was modified by the pilot himself, with a small elastic band behind his head so that it fitted very tightly under his helmet. This particular frame did not slip but the Dutch frames which are the same as the RAF frames do have a tendency to slip either up or down. The American frames do the same thing, so I would fully support Dr Draeger in his theory that contact lenses would be superior but then there are also disadvantages with contact lenses. It is very costly for the organisation and some of the pilots do not like them.

Brennan UK: The new variant of the RAF spectacles which will shortly come into service will have changed sides which offer better retention, and in addition, incorporate a slot so that if you wish to wear a band you can.

Rouwen NE: I have some comments on the Dk values Dr Cloherty mentioned on his slides and the rejection of the hard contact lenses, because the Dk value of the lens we use is 16.7 and that is almost as good as the low water content soft lenses and besides that there are new materials available for hard contact lenses with Dk values of 13, (Boston form material) which will probably be suited for extended wear. The problems with reduced wear time of hard contact lenses are not encountered in our experience, because the pilot can wear his contact lenses as long as he wants, for all his waking hours. Only during sleep does he have to remove them.

Biggelaar NE: Yes, I would like to add one feature which was not part of the lecture Dr Punt has given. Apart from evaluation in the human centrifuge, the lenses (SIL - 02 - FLEX) were also evaluated in the hypobaric chamber and they performed very well under explosive decompression and high altitude conditions.

Verona US: I have one question for the Group Captain. As a contact lens wearer one of the problems that I frequently have concerns quality control and degradation with time. Could you comment on your experience on the quality control from the manufacturers, particularly with curvature and power and did they degrade over time?

Cloherty UK: Concerning the Dk factor, you are quite correct, there are new oxygen permeable materials coming on to the market all the time. The manufacturers claim that these can be worn as extended wear lenses. I estimate it will take three years to evaluate these new oxygen permeable polymers. You could argue that you could use micro corneal hard contact lenses, of the proper oxygen permeable polymer, as extended wear lenses. I would not agree with it, but if proved successful then these could be used as extended wear lenses. In answer to the second question. The quality control in the Scanlens 75 lenses was found to be good. I think we had to return about 4 lenses because they were of incorrect power or radius, so that in our experience, with that one manufacturer, they were good.

Verona US: And did they stay pretty consistent over the life of the lens?

Cloherty UK: Yes.

Brennan UK: I cannot let the opportunity slip of having a word with Professor Draeger about his spectacles. Did you encounter any problems with fast jet aircrew because you gave them an executive style segment, as this would completely deprive them of lower lateral vision and stop them seeing the flaring of the runway? Did you have any complaints?

Draeger GE: In fact, the model shown for fighter aircraft has not been flown so far. We built experimental designs and checked them in the cockpit environment but they have not yet been flown, whereas other types have been flown.

Brennan UK: The other question. When you have multi segment lenses do you find that people complain about prismatic jump as they go from segment to segment? Also in the spectacles which you showed which had reading segments in the upper quadrant, did you have any complaints about restrictions to the peripheral field in collision avoidance and so forth?

Draeger GE: Middle-aged aircrew have not complained about these invisible segments and concerning the sidewards restriction to the field of view when looking straight ahead, it is just a matter of practice to

overcome this little field defect in the upper right or left side, this is not what people really complain about. Astigmatism is less than with Varilux lenses, there the complaint was really obvious.

Brennan UK: I agree with the difficulties in using progressively powered lenses.

Monaco US: It has been suggested that sunglass wear may reduce the progression into retinitis pigmentosa. Do you think that some of your data may be applicable to that? Further if your hypothesis may be substantiated by using patients with varying degrees of retinitis pigmentosa to elicit a differing Stiles Crawford effect?

Zwick US: Yes. When we started this study we approached the problem as though we were dealing with low level light effects, because the environmental light levels that we actually had to work with were just not bright enough, we did not see light effects. We saw an effect with sunglasses though. In some other work that I did not report we were able to get a light effect from bright Californian skies, but if I wore my sunglasses I got a reduction in sensitivity. It is hard to know whether we are on the verge of a damage effect which might relate to what you are talking about, or whether we are dealing with some sort of ability of the rods to protect themselves and how these things are related I cannot say now. It has been suggested that sunglasses may help to protect retinitis pigmentosa sufferers, it all depends on what retinitis pigmentosa really is. I do not know that there is any evidence that links retinitis pigmentosa with light effects, is there?

Brennan UK: Retinitis pigmentosa is an hereditary disease, it is not caused by exposure to light.

Biggelaar NE: I would like to ask an opinion of Dr Draeger about the feasibility of supplying multi focal glasses to a fighter pilot. We have in our inventory maybe 10% of the fighter pilot population who need glasses and they are fitted with bifocals. I do have concern about presbyopic pilots flying in fast jets. We do not fit them with executive line glasses, they use a D segment for the near correction. Now I find that it is very critical for a F15 or F16 pilot where the upper limit of the reading correction is situated. It has to be fitted to the pilot related to the position of the seat, to the upper limit of the cockpit and for sideways vision as you are landing you need to have a lower lateral vision. I would never recommend an executive line frame for a presbyopic fighter pilot.

Draeger GE: You are correct with regard to the upper border of the reading segment. In my glasses the middle segment relates to the top and bottom of the instrument panel and the bottom segment is solely for reading small print and charts. This is fitted to my face and relates to the panel position in my aircraft. When flying another aircraft I am very uncomfortable using these lenses as the panel configuration is different and this is what counts. You have to fit the individual lens to the specific pilot's working position and you need to place him in the cockpit and to measure the angles and to mark the lens. Then they have to be fitted and at the end you can adjust the frame by 1 or 2 mm up or down. This is the way it works and then the pilot will accept the lens, otherwise it is a hazard. You are completely right.

Biggelaar NE: Especially when talking about high performance fighters I do not think it is advisable to let an older presbyopic pilot fly with a trifocal. There are so many reasons to become disorientated in a modern fighter aircraft. One of the reasons is spectacles, spectacle frame plus the parallax that you have from two different lenses.

Draeger GE: Impaired vision is another hazard especially if he is unable to read his charts. In night flight you require perfect corrective spectacles and for the older man aged above 45 years, trifocal lenses are necessary. Bifocal lenses are inadequate. Only a few men of this age and above are fighter pilots. In addition they may require their distance segment to be tailored to allow lower lateral vision dependent upon the side transparency border.

EYE PROTECTION AGAINST INTENSE LIGHT SOURCES

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Summary

The assessment of modern techniques for the protection of the eyes against laser radiation must begin with the careful evaluation of these stimuli within the context of impairment of useful work. Occupational safety and health standards were designed to define exposure limits of laser systems to prevent damage. However, an eye hazard may not exist within some exposure conditions (e.g. glare, dazzle or reversible scotoma) in which functional vision impairment could result in job performance failures. Additionally, eye protection devices should not induce impairment properties.

It is within this context that our research program has been designed. The identification of laser threats, effects on functional vision and eye protective device properties are important considerations for successful aircrew performance. The vast array of intense light sources which represent threats to functional vision, introduces significant challenges for this research area.

The experimental assessment of functional vision as a result of laser exposure represents hazards which require special precautions to avoid serious injury. Our laboratory has developed a research plan which incorporates animal and human experimentation with mathematical modeling techniques to reduce the risks inherent in the study of high energy light sources. The goals of this program are related to safety and protection. The studies to be reported here include those which relate to the amount of functional vision decrements which occur following laser stimulation, as well as studies in progress on the protective measures to enhance visual performance.

Retinal impairment caused by a laser is most severe when the energy is deposited on the fovea, and permanent blindness results from these large thermally induced lesions. Such catastrophic hazards demand careful consideration for any research proposal in which human or animal subjects are involved. The research strategy of laser induced decrements in functional vision have required special justification and review of each protocol as well as careful post hoc analysis of human accidents and a thorough review of the few human experimentation efforts which have occurred.

The review of 23 human accident cases reported by Wolfe (Ref.1) covers laser exposures for several wavelengths and energy density ranges. His paper includes a scheme for grading the severity of damage with corresponding decrements in visual acuity. The size of lesions reported for the laser parameters correlate well with the animal experimental evidence for structural eye damage as well as the animal experimental evidence for changes in visual acuity. Such general confirmation of the animal to man extrapolation for laser induced eye damage and functional effects increase our confidence in animal data for laser parameters for which no human accident cases exist. Thus, statistical studies of damage thresholds such as the minimum lesion observable by ophthalmoscopy which have been accomplished using nonhuman primates can be used as a standard reference point. That is to say, one can reference the threshold value (ED 50 minimum lesion or ED 50 Hemorrhagic lesion) in terms of some multiple of the reference value (e.g. 10 X ED 50 ML).

The impairment of functional vision with laser radiation can be produced with either single or multiple pulse exposures. Indeed, the data clearly reflect that shorter pulse widths cause more retinal damage at a given energy density. The safety standard AFOSH 161-10 (Ref. 2) reflects the slope of this curve. Additionally, multiple pulses will be perceived as continuous (CW) when the pulse repetition rate exceeds the critical flicker fusion threshold. In this context, intraocular scatter of light becomes a very significant event. In the short pulse width single pulse laser radiation exposure intraocular scatter is, by definition, a very brief event which contributes to the duration of the after image as a function of the magnitude of the total energy. However, in the multiple pulse or CW case, intraocular scatter assumes greater significance. This phenomenon was first described as blinding glare by Holladay in 1926 (Ref.3). More recently a variety of terms have been added to describe the performance decrements attributable to intense light sources (e.g. disability glare, discomfort glare, veiling glare, etc.). Events which disrupt vision can be classified as (1) retinal damage, (2) flashblindness, (3) glare, or (4) startle. Some experimental evidence exists for the disruptive properties of each class of these events. Threshold values for retinal damage classes and safety for short pulses typically occur at log unit intervals. For example, the maximum permissible exposure limit for the 1.064 wavelength at 20 nsec is 0.05 microjoules, the ED 50 for minimum visible lesion is 0.5 microjoules, and the ED 50 for hemorrhagic lesion is 5.0 microjoules. This log relationship becomes significant in the determination of the protective eye wear values.

Biological variability will always prevent a precise definition of the magnitude and duration of the functional vision loss associated with a given set of laser exposure parameters. However, within reasonable limits it is possible to predict the functional vision consequences of laser exposure conditions noted above. The mission determines the amount of vision which is required, and it is possible to specify the amount of protection necessary to protect minimum acceptable levels of visual perception following laser exposure.

The most common methods employed for laser protective eyewear involve concepts of absorbtive or reflective filters. Spectral distortions can be anticipated which will produce a degraded image quality. In addition to the spectral issues, configuration issues (spectacle vs. visor) can determine user acceptance attitudes. Risk vs. benefit analysis is an important aspect of the evaluation of a particular device for a specific purpose. Protection in the form of filters will of necessity distort color perception if the visible spectrum is involved. In all probability, the distortion problem will increase if more than one wavelength is eliminated or reduced from the visible band. Distortions can be minimized by building visors with very narrow band rejection characteristics (e.g. notch filters). These goals stretch the current state of the art when the requirements specify very narrow rejection bands (e.g. one or two angstrom units) coupled with very high energy rejection requirements (e.g. above 4 OD). Obviously, the narrower the band of visible light which is removed, and the least energy removed from the visible spectrum, the least distortion of perception. Accordingly, the protection is also limited.

The selection of the amount of energy rejection required must be based upon an assessment of the power available to cause damage as well as the degree of protection which is required. That is to say, if the degree of protection required is to limit the total energy entering the eye to the maximum permissible energy (MPE) as determined by a safety standard such as AFOSH 161-10, and the threat device has high power, then, in all probability, one must accept some color distortion.

The total elimination of the wavelength of interest might not be the most desirable option. Given the capability to limit the total energy entering the eye to safe and non interfering levels might give valuable information about the number and location of the hostile laser device(s) for counterattack.

Visual perception is one of the most important skills on the modern battlefield. Just as inappropriate protective eyewear has a high probability of degrading vision, so does the proper device have the opportunity to enhance battlefield performance. A potentially blinding laser might be easily detected with the proper protective eyewear. If the optical density is too great, the device would not be detectable. Alternately, if the optical density is too low, the observer would experience flashblindness glare or eye damage.

Olson and Sivak (Ref. 4) performed studies to measure performance as a function of glare intensities from discomfort to disability. These data reflect the dependence of the task upon the glare phenomenon. The task (driving an automobile) might be successfully completed with 1 or 2 seconds of disability glare whereas other tasks (flying high performance aircraft at low altitudes) might result in performance failure with equal glare intensities.

Finlay and Wilkinson (Ref.5) demonstrated that glare adversely degraded high frequency targets on a contrast sensitivity test. Such data imply that identification of very small targets would be more difficult to detect under glare conditions than larger targets. Wolf (Ref.6) presented data to indicate that glare becomes a greater problem as a function of the increasing age of the observer, and he concluded that the difficulty accelerates at age 40.

Examination of the literature on performance decrements as a function of pulse length reflects increasing evidence that a single short pulse produces afterimages lasting a few seconds (Ref.7) whereas it now appears that pulse trains or CW events will produce disruptive effects on performance during the exposure at extremely low energy densities (Ref.8). The literature on tracking task decrements as a function of single short pulse laser radiation indicates very high energy densities are required to produce large performance decrements in a high percentage of cases (Ref.9, 10).

An acceptable proposal for protective eyewear must minimize the undesirable aspects (e.g. impair performance due to visual distortions, quality, hue, etc.) while providing the maximum protective qualities.

Morris (Ref.11) described a test plan for the assessment of protective eyewear which included clinical tests of visual acuity, stereopsis, contrast sensitivity, visual fields, dark adaptometry, and Macbeth color threshold test. Additional tests include experienced observers evaluations of wearability and visibility. User acceptance is particularly important in the evaluation of these devices (Ref.12).

In summary, the selection, evaluation and employment of laser protective eyewear is particularly threat directed and dependent upon user acceptance. Any device is likely to produce undesirable side effects, and reduce the quality of visual perception.

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Calculations on Technical Requirements for Protection Devices against a Nuclear Light Flash

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Summary:
Preliminary calculations on the requirements for protective devices against permanent retinal burns caused by nuclear detonations were based on a simplified model which also has been used for this study. The present paper deals essentially with computations concerning the reversible flash blindness of flight crews caused by a nuclear explosion as well as the resultant technical requirements to be met by antiflash eye protection systems. In the low-yield nuclear range the computations led to shutter times which are technically unfeasible at the present moment. Therefore, additional computations were made to determine the periods of blindness occurring when technically feasible antiflash eye protection systems are used. They were then compared with the periods of blindness to be expected under identical conditions but without antiflash eye protection systems.

1. Introduction

During a nuclear explosion a considerable portion of the released energy is emitted in the form of thermal and visible luminescent radiation. Even at great distances from the point of explosion this radiation may cause either transient blindness in an observer or - in the case of greater exposure - irreversible retinal burns. Transient blindness is caused by the visible part of the emitted radiation spectrum whereas permanent damage is, in addition, due to the infrared spectral range passing through the eye medium.

In order to prevent and/or limit this ocular damage various protection systems are being developed which are based on different physico-technical procedures.

These eye protection systems are either so-called passive protective filters the permanently low transmission of which constitutes a continuous obstruction to vision or active anti-flash protection systems in the form of optical high-speed shutters actuated either electrically by the flash or directly by the UV part of the radiation. The technical requirements to be met by such systems have to be computed by taking the ophthalmic exposure values of the retina of the human eye and the optical radiation parameters of nuclear explosions as a basis.

For the prevention of permanent ocular damage such technical requirements were established in the Finabel document FIN DOC A/75/1 with 3 different exposure limits for the retina being predetermined and derived from the maximum energy density radiated upon the retina without causing permanent damage (Ref 1). The following exposure limits were used:

0.1 J cm^{-2}, according to Ref 2
0.5 J cm^{-2}

and a time-dependent exposure limit determined by Ham et al. by means of experimental studies performed on the eyes of rabbits (Lit. 3).

Here the enormous influence of the predetermined exposure limit exerted on the technical requirements to be met by optical high-speed shutters in view of shutter time and optical density under blocking conditions became clearly visible.

However, these requirements can be met in any case by existing protective devices such as PLZT, having a shutter time around 100 µs. Matters become more complicated in the case of reversible blindness, as there is a functional connection between retina exposure, recovery time and subsequent visual tasks to be accomplished.

In the meantime an extensive literature study has been carried out in France involving the comparison and evaluation of existing ophthalmic works on this subject. The results obtained allow the computations of the technical requirements concerning antiflash eye protection systems to be extended to the protection against reversible blindness.

The following investigations should help establish such sets of technical parameters for some concrete cases. As even transient blindness renders the piloting of aircraft extremely difficult, this study deals exclusively with the situation of a pilot who, after being blinded by a nuclear flash, must be able to recognize and read the aircraft instruments after a certain recovery period. To present a particularly critical situation, a night flight was chosen (night-adapted eye, illuminated instrument dial). First of all, technical parameters (shutter times for different optical transmittance values under open conditions) for antiflash eye protection systems were to be worked out on the basis of given visual tasks and the maximum admissible recovery periods.

In a second phase obtainable recovery times for given visual tasks were to be computed by using realistic working data of shutters of protection systems.

2. Parameters

2.1 Radiation emitted by the fireball

Computations of the intensity and spectral distribution of the thermal and light radiation were based on the laws of radiation for the black body (Ref. 2). To demonstrate the time-dependent temperature variation of the shock wave (1st impulse) and the fireball (2nd impulse) the graphic representation devised by Glasstone and Dolan was used (Ref. 5).

The influence of the yield exerted on the time-history was computed by the formulae indicated in the NATO document EM1 (Ref. 6).

2.2 Threat criteria

The minimum distances from the point of explosion for which an antiflash eye protection system should be designed result as so-called critical distances from the distances from ground zero within which there is a 50 per cent probability that the weapon system - the aircraft in this case - will be lost due to the influence of the active nuclear components with the longest range. These critical damage radii are shown in Figure 1 as a function of the yields in the 0.1 - 1.000 KT range. In the lower yield range up to approximately 90 KT the critical component is the damage to electronic systems caused by the neutron- and γ-radiation impulse (TREE = Transient Radiation Effects on Electronics) whereas in the intermediate range of up to approximately 200 KT it is the damage caused by blast, and by thermal radiation in the upper yield KT range (Ref. 5, 6, 7).

The establishment of these curves was based on the following threat situation:

- A combat aircraft is flying low at an altitude of 200 ft towards the point of explosion of a nuclear weapon with the fireball being in the pilot's field of vision.

- The altitude where the maximum pressure damage occurs is assumed as the height of burst of the nuclear weapon This altitude may be computed by the formula

(1) $h_o = 60\sqrt{Y^{1/3}}$

where

h_o = height of burst where maximum blast damage occurs

Y = Yield

2.3 Atmospheric transmittance

In accordance with the FINABEL agreement (Ref. 2) a visibility range V = 20 km was taken as a basis to determine the atmospheric transmittance as a function of the distance.
This leads to the expression for the transmittance T(r) over a distance r:

(2) $T(r) = e^{-2.9r/V}$

$T(r) = e^{-0.145\ r}$

where

T(r) = transmittance
V = visibility range, in this case 20 km
r = distance

Atmospheric scatter phenomena were not taken into account; interest was focused exclusively on the direct luminous radiation emitted from the centre of the explosion (shockwave, fireball).

2.4 Eye parameter

According to the FINABEL agreement (Ref. 2) the blink reflex delay was assumed to last 170 ms. In all calculations of the retina exposure the retinal illuminance was integrated over this period. As - owing to the greater vulnerability to blindness - the eyes were examined under night adaptation conditions, a diameter of the pupil of 7 mm and a spectral photosensitivity V' (λ) according to Figure 2 with the maximum value of the photometric radiation equivalent for scotopic vision K'_m of 1795 lm W^{-1} was used (Ref. 4).

Figure 3 also shows the curve for the transmittance spectrum of the eye medium in front of the retina.

2.5 Blindness

In the case of reversible blindness the term "recovery time" refers to the period during which a particular visual task cannot be accomplished subsequent to an intensive irradiation of the retina. It is a function of the time integral of the retinal illuminance (exposure of the retina), the predetermined visual task and the adaptation condition of the eye. Moreover, this functional connection is subject to intense individual fluctuations.

The results of an extensive literature study and analysis were clearly laid down in the FINABEL document FIN DOC F/77/N (Ref. 8). The visual task chosen consisted of recognizing self-luminous objects against a dark background with 3/10 visual acuity. Moreover, the investigations were confined to the dark-adapted eye. The result is available in the form of 2 curves. The first curve shows hte relationship between the retinal illuminance and the recovery time for a firm object luminance L = 0.3 nit. The second one contains the respective correction factors for other luminances.

These curves were re-drawn by using the pertinent SI units; the first one was extrapolated up to 7 . 10^{-7} lms cm^{-2}. Although this extrapolation towards low retinal illuminance may well be contestable, it is the only possibility at present of making estimates in the field of short recovery times.

2.6 Visual task

The visual task chosen consisted of recognizing illuminated aircraft instruments with white lettering on a black background with the night-adapted eye having 3/10 visual acuity. According to STANAG No 322e AI lettering and needles were considered self-luminous objects with the luminance prescribed in this document (Ref. 9). As the brightness of the instrument lighting is usually adjustable, both the maximum value L_1 = 3.43 cd m^{-2} and the half value L_2 = 1.72 cd m^{-2} were taken into consideration. In accordance with paragraph 2.8 a reduced open transmittance T_o = 0,25 was assumed for some of the evaluations. Since the reversible systems return to this transmittance value after the shutter period also the curves for L_1^* = 0.25 L_1 and L_2^* = 0.25 L_2 were entered to take account of the seemingly reduced object luminance.

The relationship between the retina illuminance and the recovery time for these four values is shown in Figure 4. 2 values, viz. θ_1 = 10 s and θ_2 = 3 s were predetermined for the recovery time required.

2.7 Technical parameters of antiflash eye protection systems

The following values were assumed as parameters for antiflash eye protection systems:

Open transmittance: T_o = 0.25 — T_o = Open transmittance

Blocking ratio: $T_o/T_s = 10^5$ — T_s = Blocked transmittance

Shutter time: τ = 50 µs and 100 µs.

The shutter process was idealized by means of a step function.

3. Computational Procedures

The computations were made on the basis of procedures described in former studies dealing with similar problems (Ref. 1, 10 - 13). As the computational process has already been explained in detail (Ref. 1) only the most essential steps are described in the following.

3.1 Thermal and luminescent radiation of the shock wave and fireball

The radiation emitted by a black body as a function of the time-dependent temperature is described by PLANCK's Law of Radiation indicating the power of the unpolarized radiation emitted per wave-length unit and unit area perpendicularly to the surface into the solid angle ω = 1 as follows:

$$(3) \quad M(t,\lambda) = 2\, C_1\, \lambda^{-5} \left[\exp(C_2/\lambda \,.\, T(t)) - 1\right]^{-1}$$

where

C_1 = 5.95 . 10^{-17} Wm^2

C_2 = 1.439 . 10^{-2} mK

$T(t)$ = time-dependent absolute temperature

λ = wavelength

Here the temperature is a function of time in accordance with Ref. 5 the influence of the yield on the time curve may be computed by the following formula:

$$(4) \quad t_y = t_{20}(Y/20)^{0.44}$$

where

Y = yield

t_y, t_{20} = Corresponding time values for the yields Y and 20 KT

The total radiated power is obtained by integration over the wavelength as well as over the solid angle $\Omega = 2\pi$ taking into account LAMBERT's LAW and over the surface of the fireball:

$$(5) \qquad \Phi(t) = 8\pi^2 R^2 C_1 \int_0^\infty \lambda^{-5} [\exp(C_2/\lambda\, T(t)) - 1]^{-1} d\lambda$$

where

R = Radius of the fireball

3.2 Exposure of the retina

Of the total radiated power of the fireball only the following fraction Φ_a attenuated by atmospheric absorption passes through the pupil of the eye:

$$(6) \qquad \Phi_a(t) = \Phi(t) \frac{\rho^2 \cdot \pi}{4\pi \cdot r^2} \cdot T_L(r)$$

r = distance from the fireball

ρ = radius of the pupil, 3.5 mm in this case

$T_L(r)$ is the atmospheric transmittance related to the distance r and the visibility range V by the equation

$$(7) \qquad T_L(r) = \exp(-2.9\, r/V)$$

When passing through the medium of the eye Φ_a is subject to an absorption and is then received by an area on the retina which corresponds to the image of the fireball:

$$(8) \qquad F = \pi R_a^2 = \pi \left(\frac{R \cdot f}{r}\right)^2$$

where

R_a = radius of the image on the retina

f = focal length of the eye, in this case 17 mm

The energy flux density $E_a(t)$ applied to the retina after correction by the transmittance factor $T_a(\lambda)$ may then be calculated (see Figure 3).

$$(9) \qquad E_a(t) = 2\pi\rho^2/f^2 \cdot T_L(r) \cdot C_1 \int_{400\,nm}^{1400\,nm} T_a(\lambda) \cdot \lambda^{-5} [\exp(C_2/\lambda\, T(t)) - 1]^{-1} d\lambda$$

As in the case of reversible flash blindness only the visible part of the irradiated light affects the eye depending on its sensitivity, the value $E_a(t)$ still has to be corrected by the maximum value of the photometric radiation equivalent for scotopic vision K'_m and the spectral sensitivity degree for scotopic vision $V'_a(\lambda)$ in accordance with Figure 2. Thus one obtains the illuminance

$$(10) \qquad E_a^*(t) = K_m V_a(\lambda) E_a(t)$$

and by integrating this time-dependent value the retina illuminance until the time t_i can be computed

$$(11) \qquad H_a^* = \frac{2\pi\rho^2}{f^2} T_L(r) \cdot K_m \cdot C_1 \int_0^t \int_{400\,nm}^{1400\,nm} T_a(\lambda)\ V(\lambda) \cdot \lambda^{-5} [\exp(C_2/\lambda\, T(t)) - 1]^{-1} d\lambda dt$$

The curves $H_a^* = f(t)$ were computed on the basis of different starting values for open transmittance and, possibly, shutter times by varying the yields for the allocated critical distances.

Calculations have been performed via the data station of WWDBw ABC-Schutz/Munster on the TR 440 computer of the Rechenzentrum Nord (Computer Centre North) der Bundeswehr at Eckernförde.

4. Results

4.1 Retinal illuminance as a function of time

As a working basis for further evaluations sets of curves were calculated with the yield being varied in smaller steps in the numerical order 1, 2, 3, 5, 7, 10 etc. between 0.1 and 1.000 KT. As an example, Fig. 5 shows one set of this type of curves for a yield of 1 KT. As in this connection especially the question concerning the technical parameters of high-speed shutters arose, the area of lower retinal illuminance values H_a^* was dealt with in detail. The following 4 situations were taken into consideration:

To ascertain the necessary shutter time:

4.1.1 Open transmittance T_o = .0 Blocked transmittance T_s = 0

4.1.2 Open transmittance T_o = 0.25 Blocked transmittance T_s = 0

To ascertain recovery times θ by predetermining technically verifiable data for antiflash eye protection systems:

4.1.3 Shutter time τ = 100 μs Open transmittance T_o = 0.25 Blocking ratio $T_o/T_s = 10^3$

4.1.4 Shutter time τ = 50 μs Open transmittance T_o = 0.25 Blocking ratio $T_o/T_s = 10^3$

4.2 Required shutter times for antiflash eye protection systems

After entering the recovery times 3 s and 10 s the admissible retinal illuminance values were taken from Figure 4. Here two different luminances of the instrument illumination were predetermined: $L_1 = 3.43$ cd m^{-2} and $L_2 = 1.72$ cd m^{-2}. For an open transmittance limited to 25 per cent the pair of curves for a luminance reduced to 1/4 was used, i.e. $L_1^* = 0.86$ cd m^{-2} and $L_2^* = 0.43$ cd m^{-2}. It should be pointed out that some of the values had to be taken from the extrapolated part of the curves.

The appropriate shutter times for complete [illegible] of light under blocking conditions can be obtained from the curves 1 and 2 such as shown [illegible] 5. The required shutter time corresponds to the time at which the retinal illuminance H_a^* exceeds the highest value admissible.

These time values were given as a function of the yield for an open transmittance T_o = 1 in Figure 6 and for T_o = 0.25 in Figure 7 and that for 2 recovery times θ and 2 object luminances L each.

4.3 Recovery times in the case of predetermined shutter parameters

In the second part of the evaluations recovery times were ascertained which occur when antiflash eye protection systems technically feasible at present are used. These calculations were based on data which are characteristic of shutters on ceramic (PLZT) and liquid crystal basis. For the open transmittance of these shutters operating with polarized light a value T_o = 0.25 was assumed. Moreover, two shutter times, viz. 100 μs and 50 μs, were chosen and a blocking ratio $T_o/T_s = 10^3$ was predetermined. The retinal illuminance occuring up to the beginning of the blink reflex under these conditions was initially determined by means of curves 3 and 4 as shown in Fig. 5. The corresponding recovery times which can be ascertained from Figure 4 are shown in Figure 8 for nuclear explosions in the 0.1 - 1.000 KT range.

5. Discussion

The required shutter times shown in Figures 6 and 7 rise monotonously, in a log-log representation almost linear with the yields. In the lower yield range, however, one obtains time values - even for

complete blockage of light under blocking conditions - which cannot be realized technically for an antiflash eye protection system of the PLZT or liquid crystal type at the moment as shutter times obtainable at present are in the region of 100 µs or, at best, 50 µs.

The sets of curves for the open transmittance values $T_o = 1$ and $T_o = 0.25$ differ only slightly. This shows that the lower exposure of the eye at reduced open transmittance is largely made up for in its effect on the required shutter times by the aggravation of the visual task to be accomplished after the nuclear flash. This, however, applies only to reversible blindness.

As the shutter times for low yields cannot be realized with the shutters available at present, the recovery times occurring when such a technically feasible antiflash eye protection system is used were ascertained in Figure 8. These values exeed the limits 3 s and 10 s in the entire yield range. A comparison with the periods of blindness occurring in the case of the unprotected eye or when a neutral filter with 25 per cent transmittance is used, shows, however, that even with the means available at present a considerable reduction in the periods of blindness can be achieved.

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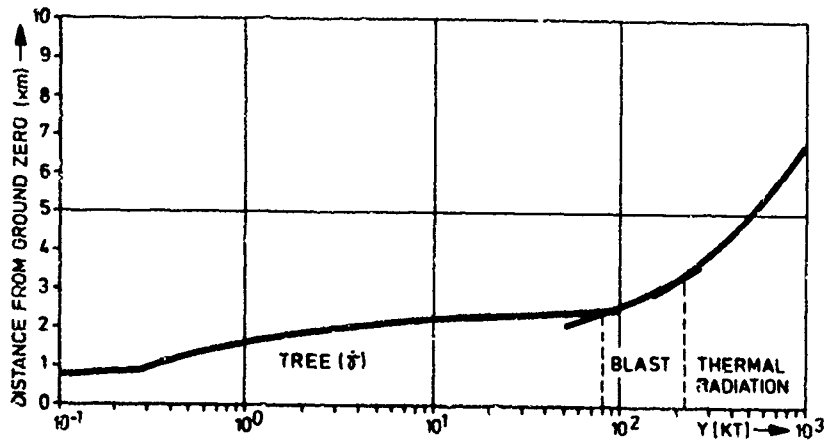

FIG. 1: CRITICAL RADII FOR AIRCRAFT AT 200 ft (AZIMUTH 0°)

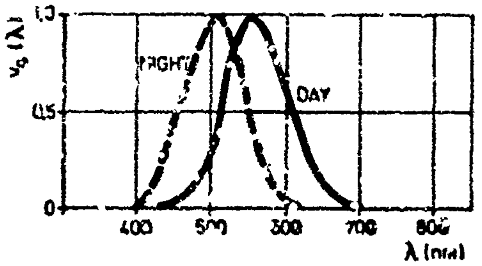

FIG. 2: RELATIVE LUMINOUS EFFICIENCY OF THE HUMAN EYE

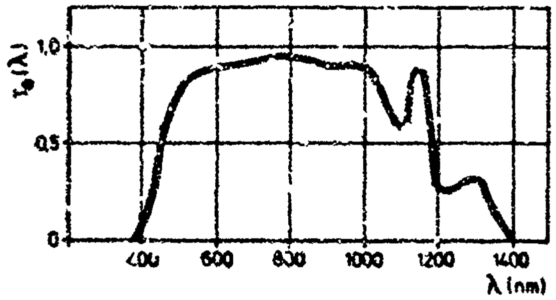

FIG. 3: TRANSMITTANCE OF THE HUMAN EYE MEDIUM

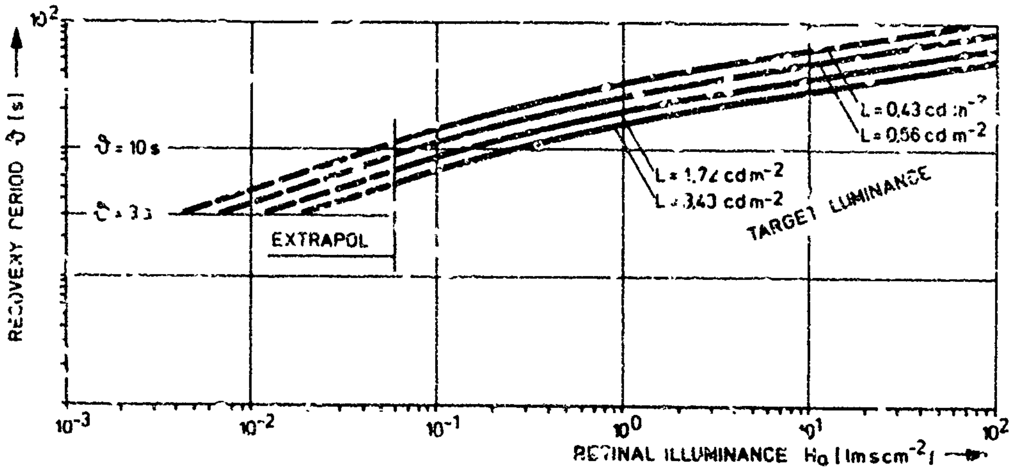

FIG. 4 RECOVERY PERIOD VERSUS RETINAL ILLUMINANCE

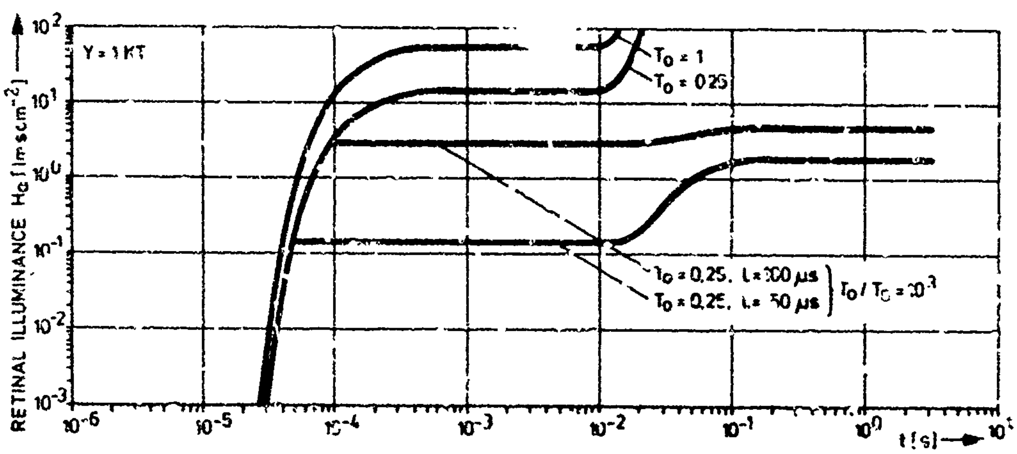

FIG. 5. RETINAL ILLUMINANCE VERSUS TIME FOR DIFFERENT OPTICAL CHARACTERISTICS OF A FLASHBLINDNESS PROTECTIVE DEVICE (OPEN / CLOSED STATE TRANSMITTANCE T_0 / T_S, SHUTTER TIME τ)

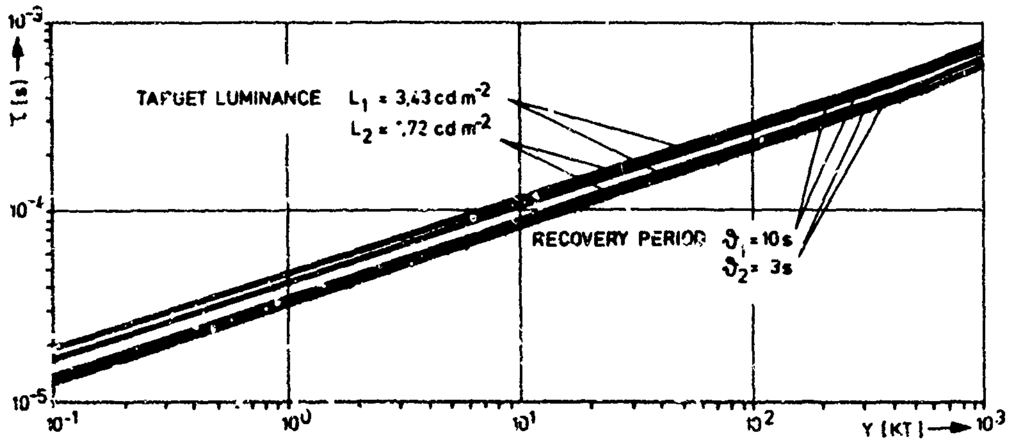

FIG. 6. REQUIRED SHUTTER TIME τ VERSUS WEAPON YIELD Y FOR DIFFERENT LEVELS OF TARGET LUMINANCE AND DIFFERENT RECOVERY PERIODS (OPEN STATE TRANSMITTANCE $T_0 = 1$)

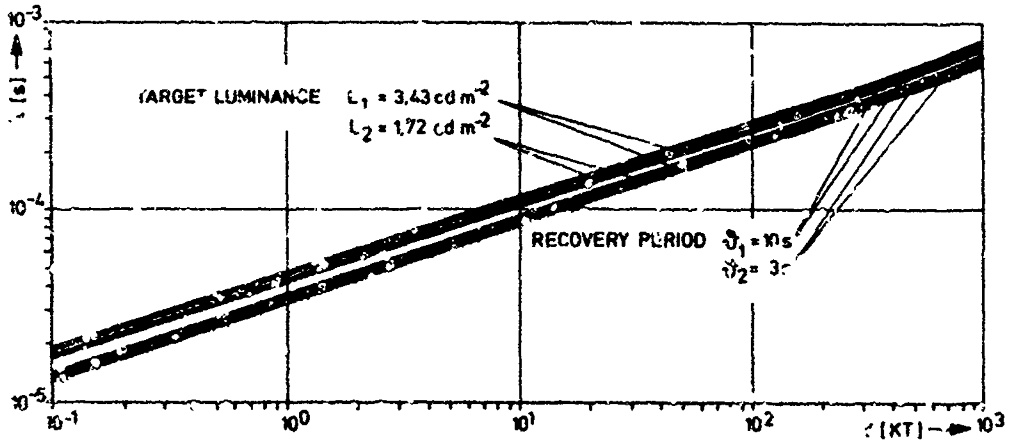

FIG. 7: REQUIRED SHUTTER TIME τ VERSUS WEAPON YIELD Y FOR DIFFERENT LEVELS OF TARGET LUMINANCE AND DIFFERENT RECOVERY PERIODS (OPEN STATE TRANSMITTANCE $T_0 = 0{,}25$)

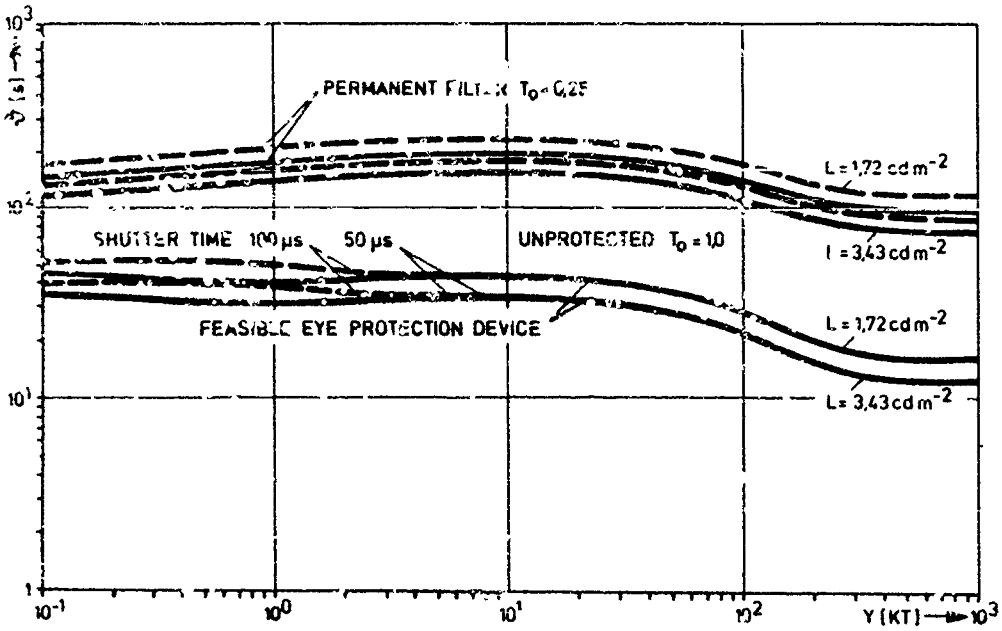

FIG. 3. RECOVERY PERIOD ϑ VERSUS WEAPON YIELD Y FOR TWO DIFFERENT LEVELS OF TARGET LUMINANCE L

German Development of a LC-Flashblindness Device

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Summary:

A research program has been conducted on the feasibility of flash blindness protection by liquid crystal techniques. The result was the development of a reversible fast optical shutter basicaly consisting of a liquid crystal cell enclosed in 2 crossed polarizers, which provided promising data for an application for flash blindness protection. Shutter times were in the range of 50 - 80 µs, an open state transmittance of 0,25 - 0,30 is state of the art. The closed state transmittance amounts to 10^{-3} to 10^{-4}.

1. Introduction

For about 5 years, the German DOD has financially supported a research project on the application of LC-(liquid-crystal-)techniques for fast optical shutters. The research work, which mainly was directed towards the development of preparation techniques, was conducted at the laboratories of the AEG-Telefunken Company at Ulm, Germany.

The scope of this work will be the development of pilots goggles, possibly a pilots visor, with nuclear flashblindness protection. This device will be triggered by an optoelectronic sensor.

2. Principle of Operation

Fig. 1 shows the configuration of an LC-cell. The LC-material, a layer of 5 or 10 microns thickness, is encapsuled between two glass plates, which carry a multiple coating of insulating and conductive transparent materials of the inner surfaces of the cell. This cell is enclosed in crossed polarizers. The transparent coatings are vacuum deposited under preferential directions, which are crossed under 90° and correspond to the transmission directions of the polarizers. The cell assembly forms a capacitor, which can be electically charged up, when the conductive coatings are connected to an electrical power source.

Fig. 2 demonstrates the molecule configuration within the LC-layer: Normally, with no electric voltage applied to the conductive layers, the boundary macromolecules are aligned with the preferential coating directions. The molecules in the intermediate space form a so-called "corkscrew" configuration. In case the electrical vector of polarized light corresponds to the direction of the boundary molecules, the light vector follows the twisted structure of the molecules which means that polarized light passing the cell will perform a 90°-rotation. In the sandwich configuration with crossed polarizers, this means the polarized light entering the cell can penetrate the second polarizer because of this 90°-rotation. This is the "open state" mode of the device.

Application of a voltage to the cell between the conducting layers causes the formation of an electric field perpendicular to the glass plates through the LC-layer. This again results in a disintegration of the twisted structure. In this mode, the molecules are aligned in a line parallel to the field, the light vector is not rotated and the light cannot pass the polarizers. This is "closed state" mode.

As soon as the voltage is switched off, the original configuration is formed again, the mode of operation changes back to "open": the operation of the shutter is reversible.

The principle of operation is demonstrated in Fig. 3.

3. Technical Data

Fig. 4 shows the open to closed switching process, recorded by an oscilloscope. The upper line represents the open state with a transmittance of about 25 - 30%, the lower the closed state which has a transmittance of 10^{-3} to 10^{-4}. The transition process starts after a certain deadtime. The complete transition time amounts to about 75 - 80 microseconds. The data have been taken by use of a device of 50 x 90 mm^2. Cylindrically curved devices have somewhat larger shutter times of about 100 microseconds. Calculations demonstrate that the speed of this type shutter is still below the principal limits, set by the RC-time of the charging network including the capacity formed by the cell.

The transition time from closed to open amounts to somewhat below one tenth of a second and takes place in two steps, which is a principal feature of the rearrangement process of the macromolecules.

The open state transmission is somewhat problematic for all the devices which operate by use of polarized light, e. g. PLZT and LC. At present, the open state transmission of our device is about 25 - 30%. The manufacturer, the AEG-Company, expects to arrive at a value of 35 - 38% by use of special polarizers and by special antireflection coatings.

The closed to open ratio of the transmission is constant at about 10^{-3}. The nominal operating voltage is 80 V ac. for a 5 micron cell. The device still operates at lower voltages, but the shutter speed for the open to closed transition is drastically decreased at lower voltages. The application of an ac.-voltage is required in order to prevent chemical polarization of the LC-material. At present, the device is operated at a 500 cps.-signal.

The operational temperature range extends from +5 °C to + 60 °C. It can be modified by using different LC-materials. A drawback of the LC-method is certainly the angular dependence of the closed state transmission of a flat LC-device. Whereas the closed state transmission, which is minimum in the central field of view, is relatively unaffected by the angle of incidence of light within 4 wide sectors of the field of view, which form a crosshaped figure, the transmission shows a maximum decrease in the 4 half-angledirections between these sectors. In these areas, the protective effect of the device is considerably lowered.

Here, the transmittance increases to open state values at an angle of inclined light incidence of $\pm$ 30° to 40°, depending on wavelength, for the 10 micron device, and of $\pm$ 45° to 60° for the 5 micron device.

Since that is unsatisfactory, a simple technique is applied to compensate this effect: Use of cylindrically or spherically curved geometry for the fabrication of the cell extends the area of high absorption over the entire field of view. Curved samples of a 45 x 45 mm^2 size have already been produced and tested, having a curvature radius of about 60 mm.

4. Special Features

The LC-method has several operational characteristics, which are of technical interest for eye protection applications:

- The operating voltage is relatively low, it is applied in the closed state mode, so a failure of voltage supply would not suddenly cut off vision.

- The feasibility to develop large area devices has been proved, using small support spacers to control the distance between the glass plates.

- The technique allows the development of curved structures, so far in order to compensate the above mentioned off-axis-characteristics of flat devices. Later on, this can be used - in combination with large area techniques - to assemble pilots visor geometries.

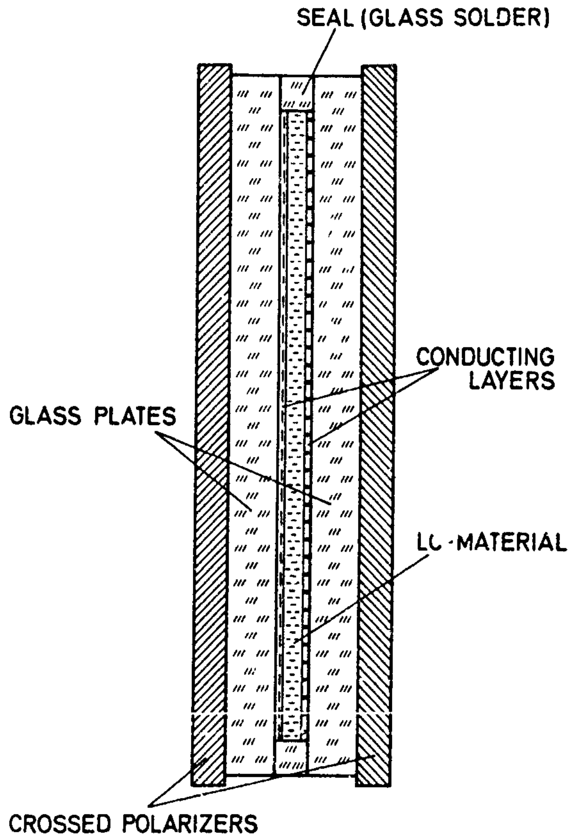

FIG. 1: LC SHUTTER CELL

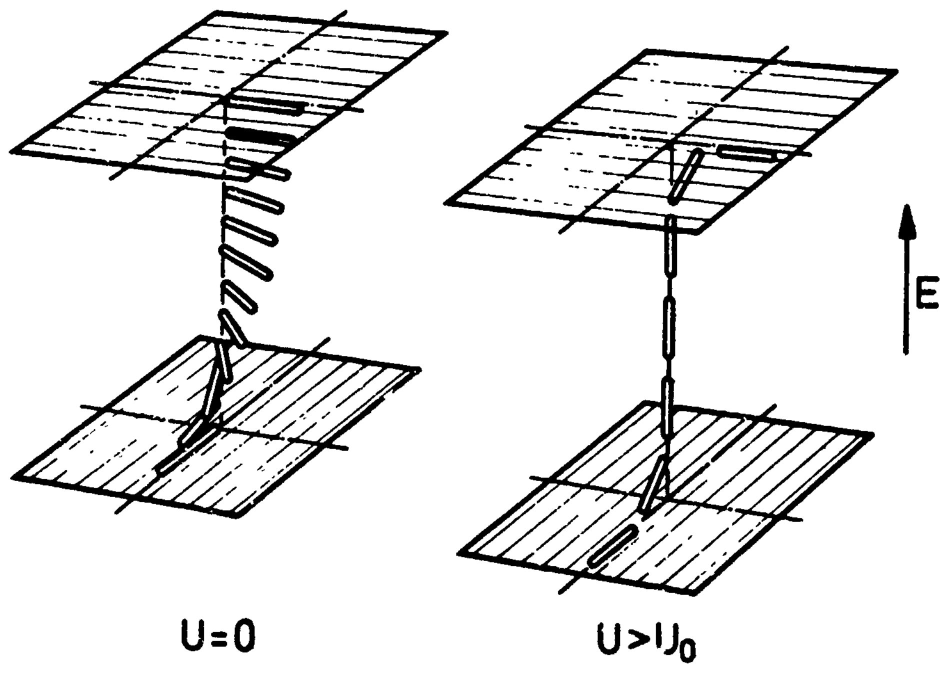

FIG. 2: MOLECULE CONFIGURATIONS IN LC-LAYER

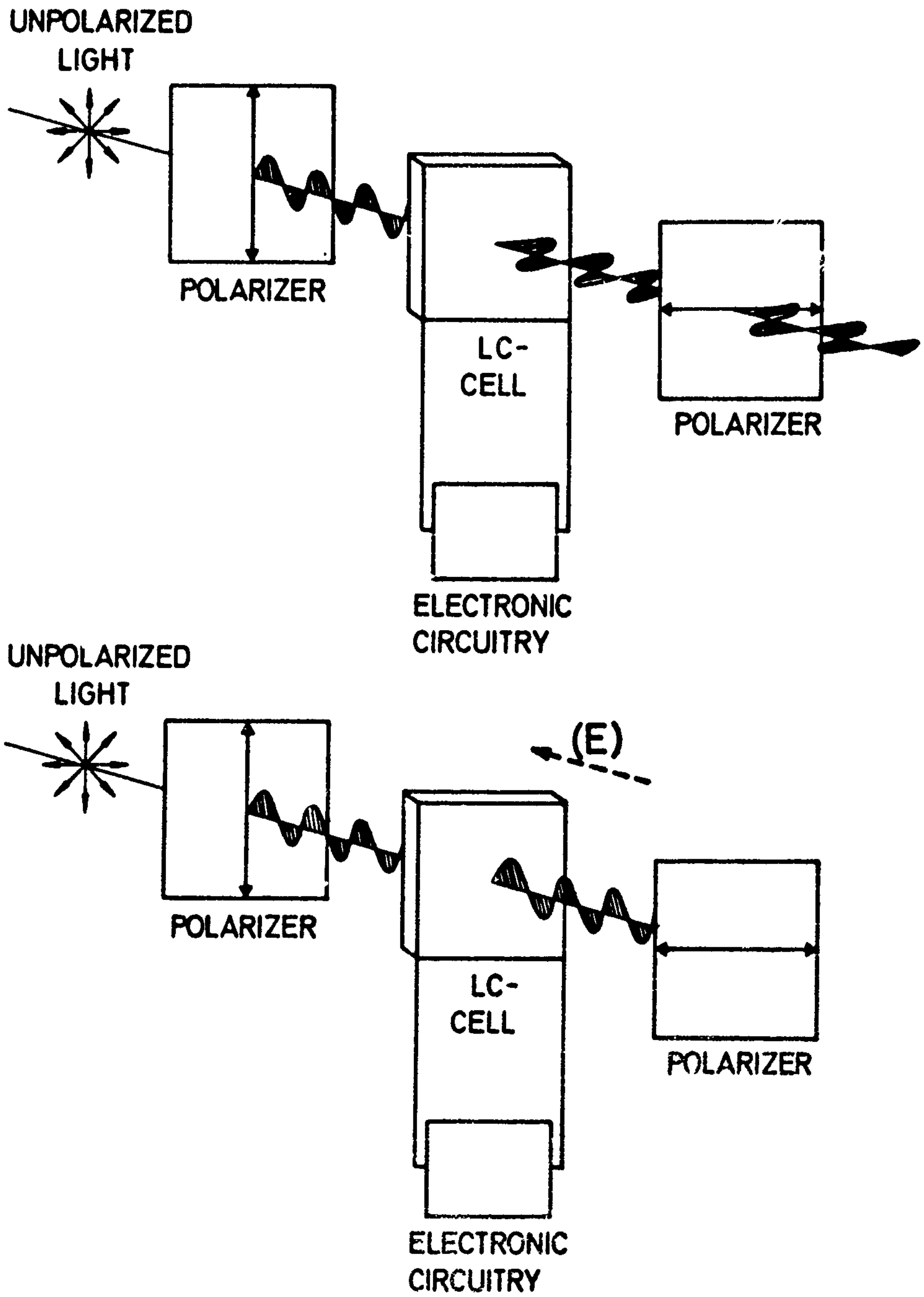

FIG. 3: LC-CELL: PRINCIPLE OF OPERATION

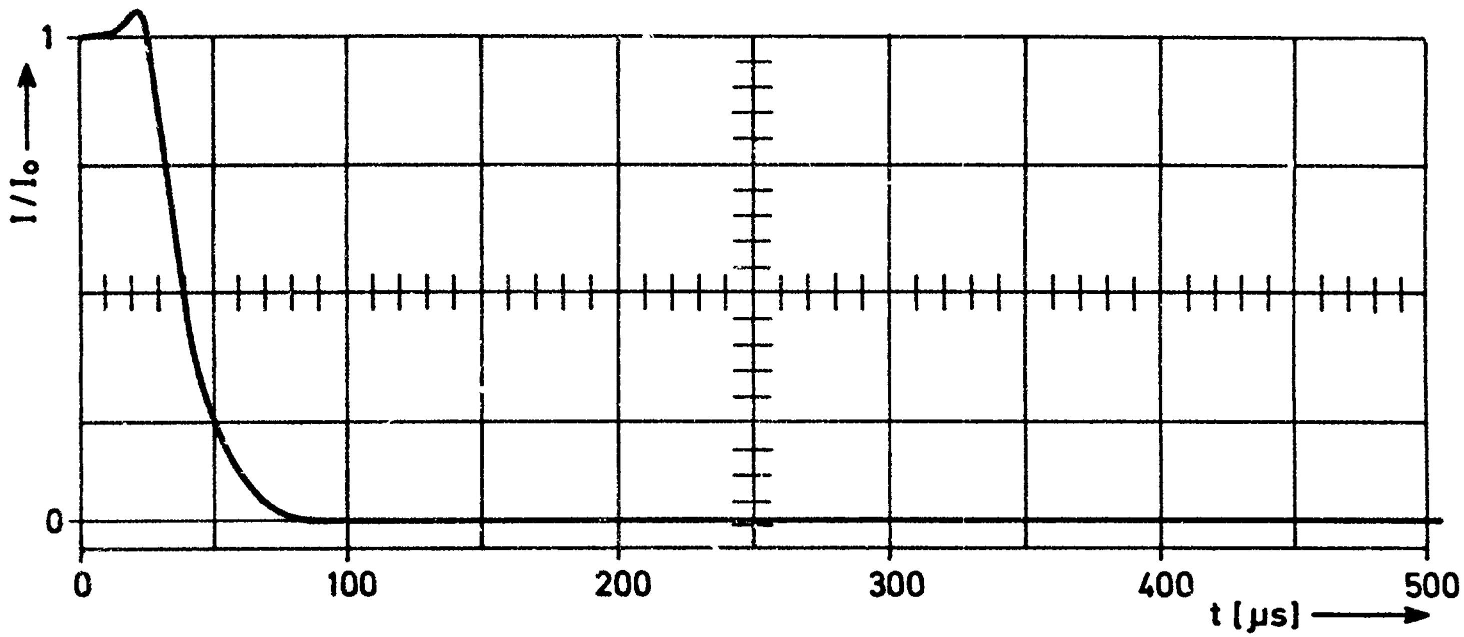

FIG. 4: LC-SHUTTER OPERATION (OPEN→CLOSED)

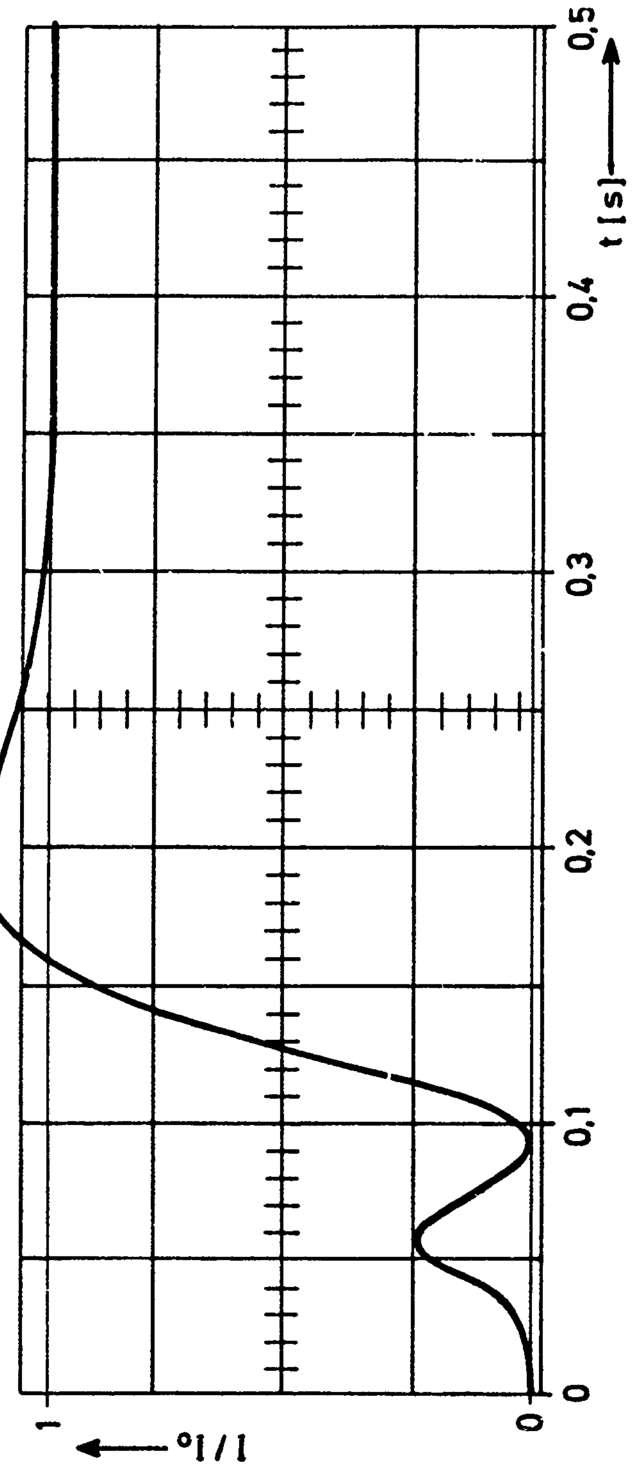

FIG. 5: LC-SHUTTER OPERATION (CLOSED→OPEN)

The Application of Diffraction Optics Techniques to Laser Eye Protection

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ABSTRACT

Development of a method of protecting the eyes of military personnel from laser radiation has been pursued for a number of years. The devices developed have marginal acceptability, particularly for aircrew personnel. Efforts underway to develop a holographic diffraction grating protection device indicate that such a device is feasible and that the requirements of high transmittance, multiple wavelength rejection and configuration suitable for aircrew use can be met.

INTRODUCTION

Lasers are being used in an increasing number of military situations. The increased usage broadens the potential for hazardous exposure of personnel and the possibility of eye damage resulting from the exposures. A number of methods of providing eye protection for personnel who work in a laser environment have been developed or proposed. Most of the methods utilize a plastic or glass absorbing filter to provide the required protection. Spectacles and goggles which have been developed for laboratory personnel have limited applicability in an operational environment. Spectacles and visors which have been developed for operational situations are marginally acceptable. The difficulties which contribute to the marginal acceptability involve both the configuration of the devices, as with spectacles for aircrew use, and the transmittance characteristics of the devices. The absorbing materials are broad spectral band absorbers, and in most cases significantly reduce the visible transmittance of the devices. When the devices are configured to protect against more than one wavelength in or near the visible spectrum, the transmittance is too low to be useable in many flight environments, and in most other operational environments, particularly in low light conditions. In addition, the spectral distortion produced by the spectrally selective filters reduces the acceptability of the devices. Because of these deficiencies, efforts to develop a more satisfactory method of providing laser eye protection in a multiple wavelength environment have been continued.

PROTECTION ALTERNATIVES

Dynamic solutions to the problem of laser eye protection have not been explored in depth because of the extremely rapid exposures which are involved, particularly if a pulsed laser is Q-switched. Other efforts to develop dynamic eye protection devices for use in much less demanding temporal conditions resulted in the conclusion that dynamic technology for use in protection against Q-switched laser pulses is not yet available. An approach which seemed to offer the greatest likelihood of success was one which could provide very narrow band, high rejection level filtering. If such a filter were possible, a fixed filter which rejected the threat wavelengths could be worn in all light level conditions if the number of threat wavelengths in the visible region were not so great that the visible transmittance would be significantly altered. This method of protection, the band rejection method, requires that the wavelengths to be rejected be specified. However, laser technology is reasonably well known so that the lasers which have high potential for use in ranging, detection, communications or even weapons can be specified with a high degree of confidence for at least the immediate future. An exploration of the possible alternatives for providing the narrow band rejection filter raised the possibility that laser technology might be applied to the problem. The goal would be to develop a band rejection filter implemented as a layered diffraction grating mirror applied to the pilot's eyewear. Such a device would meet the requirement for a multiple wavelength laser eye protection device.

HOLOGRAPHIC DIFFRACTION PROTECTION DEVICE

Theoretical analyses of the feasibility of a holographic device involved the determination of the rejection efficiency which might be expected in a diffraction grating, or hologram, the physical configuration which would be required to provide the necessary protection, the possibility of using multiple holograms to provide the multiple wavelength protection required and the minimum wavelength bandwidth which could be provided in conjunction with the high rejection levels required. The analyses indicated that the high efficiency rejection, the narrow wavelength bandwidth, the wide angular bandwidth and the geometric configuration of a visor or spectacle applied device were feasible, and that the technical problems involved in producing such a device were solvable.

In order to have a satisfactory eye protection device, it is necessary that a narrow constant wavelength rejection band be provided for a relatively wide angular band. The

constant wavelength protection is necessary if the mission of the device is to be fulfilled and to avoid spectral distortions across the visual field. Two factors determine the angular and wavelength band rejection of a diffraction grating. They are physical parameters, such as grating layer spacing and index of refraction, and the device geometry. The processing methods used to fabricate a holographic grating determine the physical parameters, and can be optimized to provide the angular coverage required but not without broadening the wavelength rejection band. However, in conjunction with the geometric design of a visor, spectacle or goggle the overall design can be optimized to obtain the angular coverage required with acceptable wavelength band rejection.

The overall optimized design is achieved when light at the design wavelength is diffracted away from the device directly back in the direction of incidence. It became apparent early in the development effort that in order to protect both eyes with a visor or spectacle, separate diffraction gratings would be required for each eye. Thus for each protective wavelength two holograms would be required. A three wavelength visor or spectacle would require at least six holograms, a four wavelength device would require at least eight holograms.

An important consideration in the design of a holographic eye protection device is the distance between the device and the eyes. A diffraction optical element depends on Bragg reflection which is angle sensitive. The rejection efficiency, therefore, is angle sensitive and the device design is constrained by that sensitivity to the extent that any incoming ray which might enter the eyes must be within the efficient Bragg reflection envelope. The range of angles over which a single point on a device must reflect is a function of the size of the effective pupil which must be protected. The effective pupil size depends on the maximum diameter of the pupil of the eye, the maximum excursion of the eyes in eye movements, the minimum and maximum interpupillary distances of potential users and the precision with which a device can be repeatedly aligned on a wearer. An example of the "pupil" which must be protected as it applied to a visor is shown in Fig. 1.

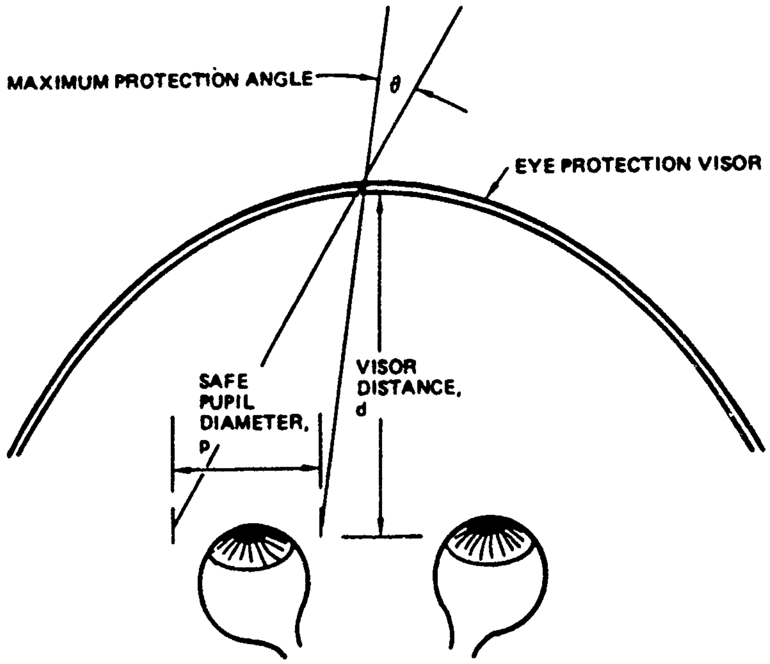

Figure 1. Pupil size and visor distance determine the maximum protection angle required. (1)

The same considerations applies to a spectacle or goggle. Fig. 2 shows the angular coverage required to protect a "pupil" for one combination of visor geometric configurations. In this instance, the maximum angular rejection at peak efficiency required is 27 degrees.

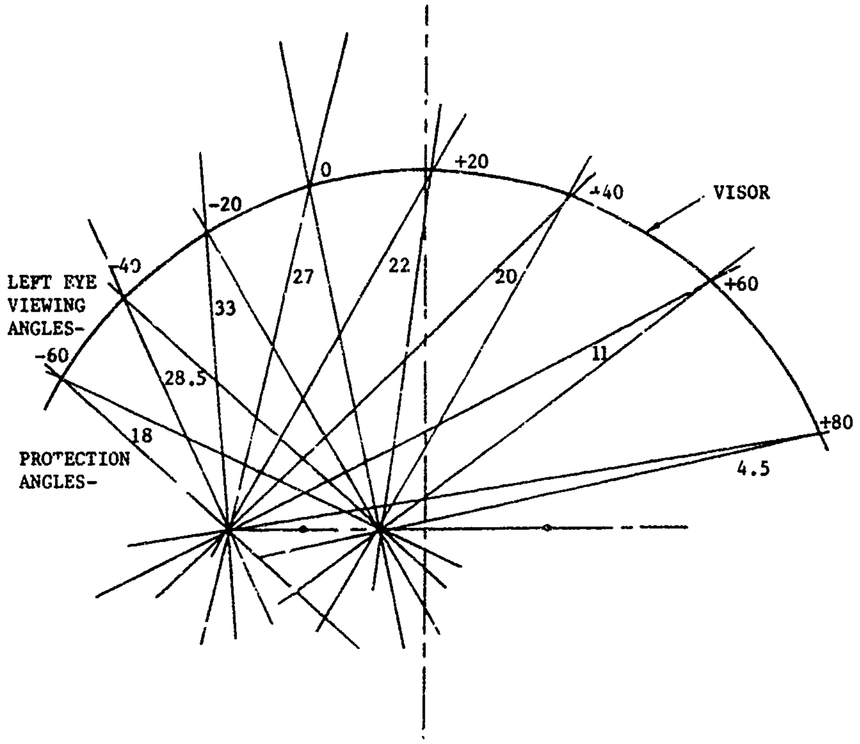

Figure 2. Protection angles necessary for 90mm visor distance, 40mm pupil and 115mm visor radius. (1)

A summary of other configurations is shown in Fig. 3. The final design of the device must be a trade-off between angular rejection of the holograms, device positioning and number of holographic layers required to protect the effective pupil.

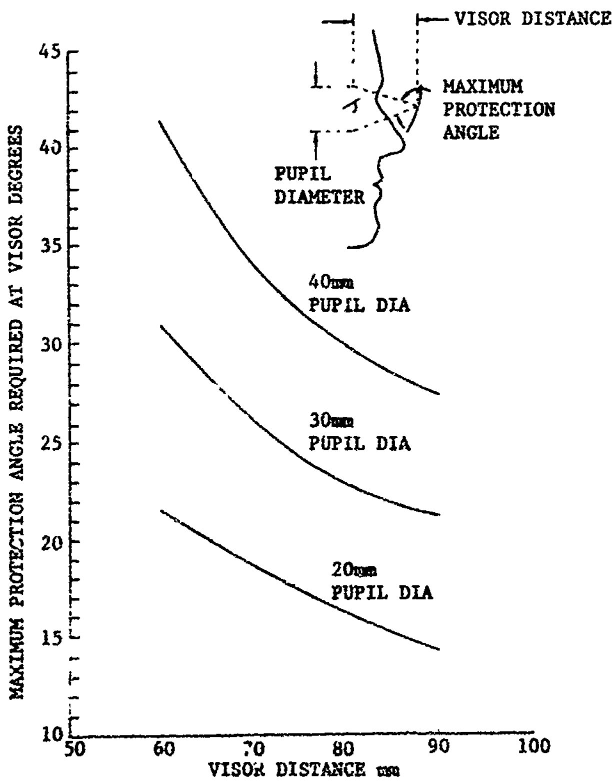

Figure 3. Maximum protection angle required as a function of visor distance. (1)

The high efficiency holograms required for protection have been constructed in both a glass mock-up and prototype plastic visors. The optical quality and rejection levels of the mock-up, are excellent. The quality of the single wavelength visor prototype is very good when it is recognized that no investment has been made in molds to form the visor or tooling to facilitate holographic layer transfers. Handling of a visor sized micron thick layer of gelatin is tedious, and a small folds can easily occur in the gelatin layers. Tooling for hologram transfer from exposure and treatment optics to the visor is essential for satisfactory visor construction. The most recent contract in this effort requires delivery of a two wavelength visor mock up.

A final area which must be considered is the stability of the protection device. Moisture is the problem which most significantly affects construction and stability of a holographic device in which the holograms are formed in gelatin. Plastics are hydrophobic. The gelatin is moist. In order for the gelatin to adhere to plastic, special treatment of the plastic is required. The gelatin absorbs moisture. The wavelength at which the hologram operates is a function of the amount of moisture in the gelatin. All of the exposures for the grating construction are made at a wavelength to which the gelatin is most sensitive and at which high exposure levels can be achieved. The wavelength at which the hologram operates is then adjusted by either adding moisture to swell the gelatin and increase grating line spacing or by removing moisture to shrink the gelatin and decrease the line spacing. When the proper moisture content is achieved, the holograms must be sealed to prevent further changes in moisture content. The problem of sealing in plastic which is permeable to moisture has been difficult to solve. A satisfactory solution has yet to be demonstrated.

CONCLUSIONS

The feasibility of a holographic laser eye protective device for fixed, specifiable multiple wavelength protection has been demonstrated. Most of the problems involved in producing such a device have been verified as solvable. Some, such as the moisture barrier, remain to be verified. Completion of the program will be expensive and decisions regarding the future of the program must still be made. The final configuration of an eye protective device both in terms of the geometric configuration and the wavelengths to be protected against will be made in the future.

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FOVEAL FLASHES AND HUMAN PERFORMANCE

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ABSTRACT

The increased use of low power lasers as rangefinders and target designators by both NATO and the Warsaw Pact troops has raised speculation about the effects of brief ocular exposures upon some facets of militarily relevant human performance. The military pilot is both susceptible and vulnerable to flashes of light in both daylight and nighttime combat. Until recently little attention had been directed toward the use of lasers as "flash" sources.

We wished to determine the role of several variables in the production of a flash which would reduce the ability of humans to detect and discriminate targets, functions which are required of both air and ground troops.

Four volunteers were exposed to Xenon gas discharge tubes with different retinal spot sizes and flash durations. The task consisted of a reaction time experiment in which the subjects detected both the presence and orientation of a striped grating which subtended 0.57^{o} at the retina. Three grating contrasts (14.3, 49.5, and 71.7%) at three pattern-background contrasts (16.7, 40.0, and 70.0% respectively) were presented in a pseudo random order. Three flash conditions were used: a retinal spot size of 0.092 mm at 0.08 J/cm^2 sr had a 2 usec flash duration, 2.94 mm, and 0.092 mm flashes were present for 500 usec at 0.11 J/cm^2 sr and 0.12 J/cm^2 sr. The results showed that the larger image size and longer flash durations produced significantly poorer performance on both the detection and discrimination tasks. For the smallest retinal spot size, and the shortest flash condition, the detection but not the discrimination times were faster than in the non-flash trials. This indicated that while the flash may have acted as a preparatory signal, more complex pattern processing remained sensitive to the flash.

While these data are for "laser simulation" flashes of brief duration, the implications for the military aviation community of directed energy use in combat may require retraining of combat pilots to avoid or reduce the effects of intense light sources.

The ability to detect objects following exposure of the eyes to very bright flashes of light has been studied extensively. These earlier research efforts (1,2) were primarily directed toward the prediction of specific flash effects as a result of viewing an atomic fireball. Flash recovery was measured for practical tasks, i.e. time to read aircraft dials, and the maintenance of flying attitude (3, 4). In investigating these variables, other aspects of flash effects were not considered important at that time. Thus, with a few exceptions (2), wavelength, retinal image size and location, duration and repetition rate of the flash were not studied in depth. In addition, precise visual attributes of the target, such as the relative contrast of the target against its background and the role of the contrast of elements within the target itself were rarely considered as variables. Specifically, the effects of a flash of light upon the perception of low, medium, and high contrast gratings against a low, medium, or high contrast background have not been studied.

During the 1960's, investigators (5) recognized luminance of the display as a critical variable. Both reaction time and recognition time were reduced as the target luminance was increased. The target most often used was a black Landolt "C", but its contrast with the background was seldom reported.

The use of bright white light sources to evaluate flash effects and recovery criteria is a first attempt to approximate the effects of brief laser flash exposures. They differ, however, in several important respects. First, a laser is coherent with essentially parallel rays of light entering the eye. This beam is then focused into a nearly diffraction limited spot of 20 to 50 microns in diameter of the retina. White, incoherent light rays spread out more rapidly, resulting in a larger retinal spot. Second, a monochromatic source such as a laser may differentially affect rods or cones resulting in recovery times that may be significantly different than those under white light conditions (2). A third difference is in the pulse width available with lasers. A Q-switched system may deliver pulses in nanoseconds (10^{-9} sec), whereas the fastest xenon flash is limited to approximately 1 usec (1×10^{-6} sec). This difference in the pulse width may also be reflected in the mode of retinal interaction (mechanical vs thermal).

Ginsberg et al (6) indicated that perhaps visual acuity is a less appropriate measure of visual function when the task required is not acuity-dependent. A more meaningful measure of visual function may be the relationship of target contrast to flash variables such as duration, retinal image size, and the subsequent recovery of both the ability to detect and ability to recognize these targets.

In the present study, we examined the recovery time to detect and recognize the orientation of gratings following a white light flash of two durations and two retinal image sizes for three levels of target-background and within target contrasts.

METHODS

Four observers gave informed consent and volunteered for this study. The display and exposure optics are schematized in Figure 1. A square wave grating was projected onto the ground glass screen (Sc) and reduced in contrast with a second beam (L2). The grating field subtended 0.57° visual angle; the surround 4.37° (square aperture). Three target contrast levels were used, 12.9, 49.5, and 71.1%. The grating contrast (black vs white bars) varied simultaneously in one of three steps, 16.7, 40.0, and 70.%. Percent contrast is defined as:

$$\frac{(\text{Target} - \text{Background})}{(\text{Target} + \text{Background})} \times 100$$

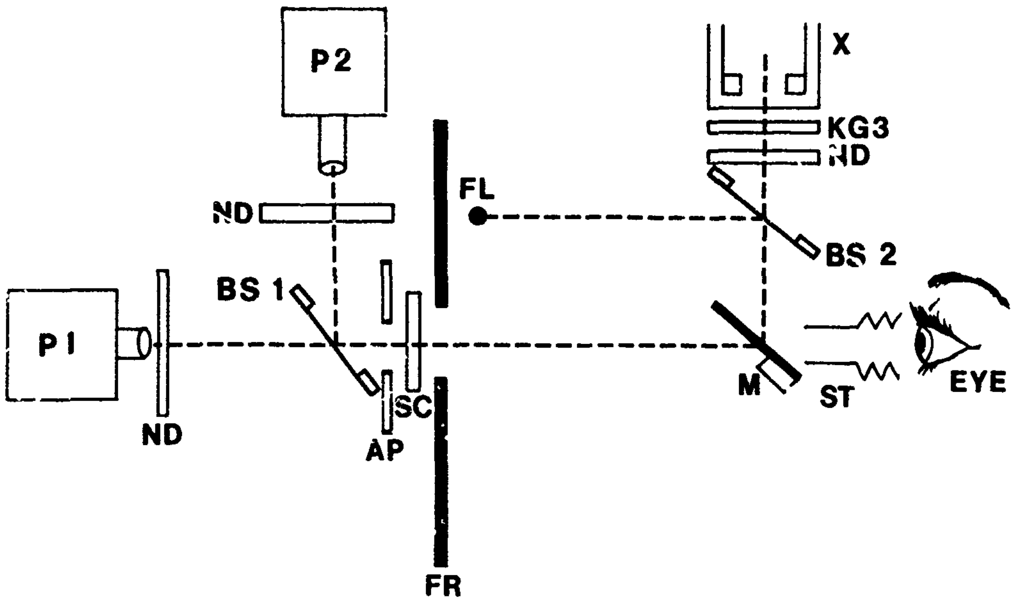

Figure 1. Schematic of optical arrangement: P1, target projector; P2, background projector; ND, neutral density filters; BS 1 & 2, pellicles; SC, ground glass screen; AP, aperture; FR, surrounding frame; FL, fixation light-emitting diode; M, swing first surface mirror; ST, sighting tube; X, xenon flash lamp position; EYE, eye position; KG3, infrared absorbing filter.

A fixation and accommodation target (FL) was optically superimposed on the grating position. A swinging mirror assembly (M) was positioned in front of the subject. It had a 4.5 msec lag time and a 52 msec swing time to clear a sighting tube aperture. A trial began with the removal of the swinging mirror from the optical path revealing the grating. At this moment, a flash may or may not have occurred.

Two flash lamps were used under three conditions. A Honeywell Auto 880 Xenon photostrobe with and without a 1.5 mm aperture, and an EGG FX280 Flashlamp. Table 1 shows the source radiation following appropriate infrared (KG-3) and neutral density filtering. Table 1 also compares the source radiance of the two lamps with the maximum permissible exposure limits (MPE) for an extended source as calculated from TB-MED 279 (7).

The volunteer was given two controls: a toggle to signal detection of the target spot, and a joystick to signal orientation of the grating pattern superimposed on the target. The controls were connected to millisecond timers. Trials were presented in

Table 1

Summary of Flash Lamp Characteristics

Lamp	*Aperture*	*Visual Angle*	*Retinal Spot Size*	*Source Radiance*	*Flash Duration*	*MPE*
Honeywell Auto 880	*(L2) 1.5 mm*	*(0.31°)*	*.092 mm*	*0.08 J/cm²sr*	*500 usec*	*0.79 J/cm²sr*
	(L3) 48 mm	*(9.9°)*	*2.94 mm*	*0.11 J/cm²sr*	*500 usec*	
EG&G	*(L1) 1.5 mm*	*(0.31°)*	*.092 mm*	*0.12 J/cm²sr*	*2 usec*	*0.13 J/cm²sr*

Table 1, summary of flash lamp size, retinal image size, source irradiance and flash duration used in the present study. These are compared to the MPEs for an extended source for the 2 flash durations. The designations L1, L2, and L3 refer to the lamp data shown in Figures 2,3, and 4.

presented in runs of 10 each at specific target and grating contrasts pseudorandomly arranged across the session for each subject. Each contrast was repeated once resulting in a matrix of 60 trials per lamp, 20 at each contrast. Flashes were presented on 20% of the trials, two in each block of 10 constrained so that no flash would occur sooner than three trials after a previous flash. A training session of 12 trials without flashes preceded each session of 60. Each lamp was run on a separate day.

Three-way analyses of variance were run on the results for detection and discrimination data separately and broken out into two-way and one-way analyses where needed. Interactions were analyzed with Bonferroni's test(8). Subject by contrast by flash/no flash interactions were analyzed as were subject by contrast by lamp differences. The flash data were normalized to the nonflash data for each subject. Means and standard deviations of flash responses were calculated from these normalized data to determine if a significant training effect existed for any lamp.

RESULTS

Figures 2 and 3 show the reaction time data for all four subjects (S1-4) for all three lamp conditions across the three target contrast levels (L, M, H). for detection and discrimination of the grating under flash (dark bars) and nonflash conditions. False responses were eliminated from the database. With the exception of the EGG lamp detection data, all flash lamps significantly degraded performance in detection and discrimination. ($p < 0.05$). Differential effects by contrast of target were shown only for the large spot Honeywell flash lamp (L3) where the lower the contrast, the longer the detection time ($p < 0.05$). For all three contrast levels, each flash lamp's effect was significant, with the 1.5 mm, 2 usec spot (L1) actually producing faster detection times than in the no flash situation. Even though the subjects were different ($p<0.01$), all showed the same pattern of effects, merely to differing degrees. Figure 4 shows the normalized and averaged trend data for the flash trials. All training or familiarization trend effects appear to be nonsignificant, as the means of the normalized flash data do not fall outside of the 95% range (dotted line) although the large Honeywell flash lamp (L3) reaction time data appear suggestive of such an effect.

DISCUSSION

Since the small retinal spot diameters (0.92 mm) approximate the flash one would receive from a laser source, the results of the two flash durations are highly relevant. For detection, the effect of the 2 usec, 1.5 mm xenon flash (L1) was negligible except in those instances where the trend actually reversed (i.e. the subject responded faster in the presence of the flash than in its absence). This difference was significant ($P<0.05$) only for two subjects. Discrimination, however, was significantly delayed in all subjects. For 500 usec pulses, the flash effects for detection and discrimination were significantly longer when compared to the no-flash situation, but ordered effects by contrast were not significant across subjects. When the lamp size was increased to 9.9° visual angle (2.94 mm on the retina), the detection and discrimination times increased dramatically and effects of contrast were apparent for all subjects.

CONCLUSIONS

The combination of small spot size (92 u) and short flash duration (2 $_{u}$sec) produced minor disruption in the observers' ability to detect and discriminate targets of varying contrasts. When the image size was unchanged and the pulse width increased to 500 usec, major differences appeared in both the response times to detect and discriminate the targets when compared to the no-flash conditions. An ordered effect of contrast was also apparent. At the largest flash field and longest duration, these effects were amplified. The relationship between pulse width and spot size has not been explored sufficiently. In these data it appears that the amount of time the eye is exposed to a flash may be more important than the actual spot size.

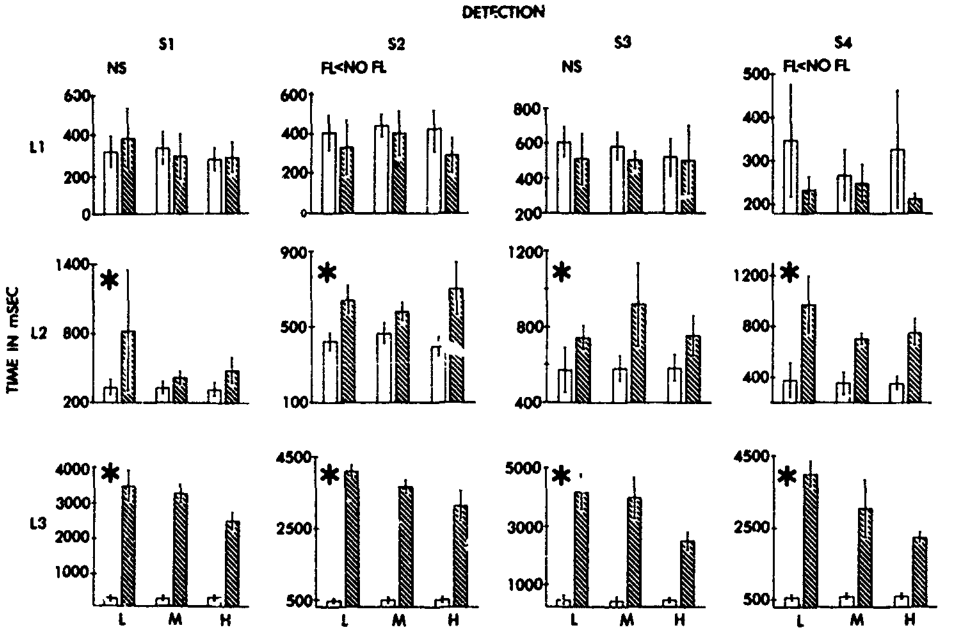

Figure 2. Reaction time data for target detection for all subjects (S1-S4) arranged by lamp: L1, EGG FX 270 1.5 mm; L2, apertured (1.5 mm) Honeywell Auto 880; L3, open (48 mm) Honeywell 880. In each panel, the first bar of each pair is the non-flash data; the second is flash data; the first pair describes low contrast target data; the second medium; the third high contrast. The error bars are ± 1 standard deviation. Note independent vertical time axes for each panel. The asterisks indicate significant differences between flash and ·› flash condition (p<0.05).

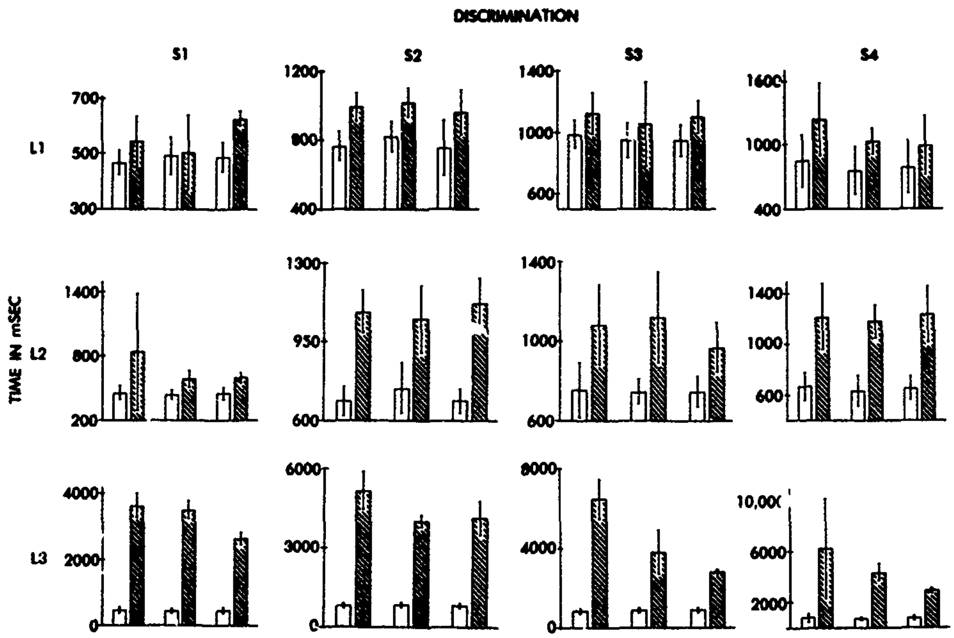

Figure 3. Reaction time data for target discrimination. (Arrangement as in Fig 2). All flash-no-flash differences are significant (p<0.05).

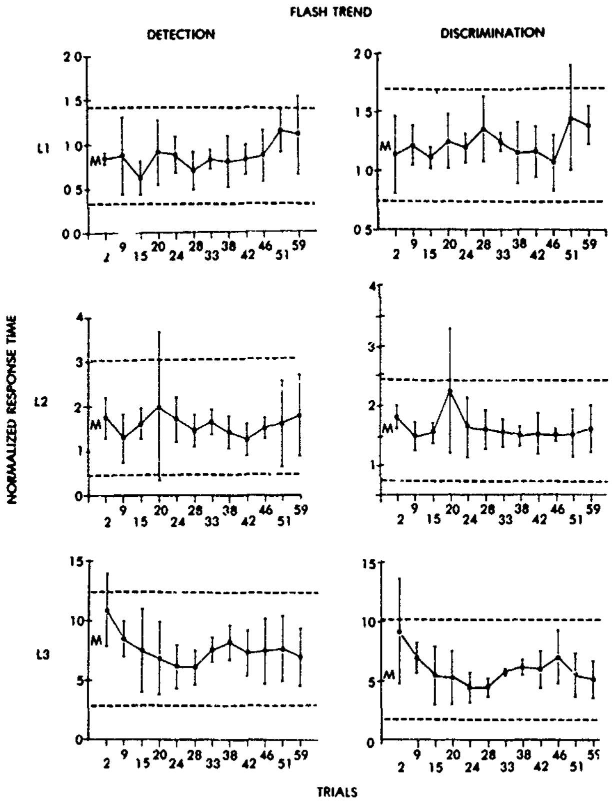

Figure 4. Means and 1 standard deviation of normalized flash target detection and discrimination reaction times as a function of flash trial for all three lamps for the four subjects. Overall mean and 1 standard deviation for the data panel are also shown. The dotted line is the 95% range of the normalized data.

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Permanent Visual Change Associated with Punctate Foveal Lesions

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SUMMARY

In order to understand battlefield hazards of laser exposure under field conditions, it has been necessary to evaluate effects of small punctate foveal lesions on visual function of non-human primates. Previous experiments have found a correlation between functional loss and foveal damage. The present investigation showed that detecting the effects of small foveal lesions --those that might be produced under field conditions-- is not an easy task. From the results of this investigation, we forsee the possibility that considerable foveal damage could occur before a measurable change in visual function could be detected with presently available visual function testing procedures. We recommend more sensitive visual function test procedures, such as clinical tests that measure both spectral and spatial resolution under threshold contrast conditions.

Normal human vision is an integral part of any specific combat scenario. Protection of the human visual sensor, as well as a thorough understanding of how noxious combat exposure conditions might alter its function, is essential to the success of any military mission.

In recent years, the combat threat from directed energy sources has become increasingly obvious. Laser rangefinders, laser designators, and potential laser weapons all pose a unique hazard to the human eye. For this reason, knowledge of how various modes of light exposure can affect vision, the mechanism of photic damage and recovery that the visual system can mediate, and development of clinical test apparatus for early and preventive ocular medical treatment have become critical mission necessities.

For many years, retinal lesions produced by intense light exposure were thought to result primarily from thermal changes produced at the retina although some early work had suggested a non-thermal damage component (1,2). Recent investigations (3,4,5,6,7) of acute intense light exposure revealed that photically induced retinal lesions could be produced by non-thermal as well as by thermal mechanisms of light damage. Other investigations (8,9) of a slightly different type, where the effects of prolonged exposure to environmental light levels were investigated, suggested that night visual function might be transiently impaired following prolonged exposure to bright environmental lighting conditions. More recently, animal investigations (6,10) have demonstrated that chronic exposure to visible spectral light at levels not capable of producing thermal retinal changes can cause significant alteration of the color vision photoreceptor mechanisms. Changes in spectral sensitivity for increment threshold criteria, for visual acuity criteria, and for retinal electrophysiological criteria have been observed following such exposure (4,6,10,11).

With the development of laser sources, another potential damage modality of light on the visual system was created. The Q-switched laser can produce pulses as short as 2-20 nsec. It may create effects that involve acoustic/mechanical shock. For visible wavelengths, Q-switched pulses may involve all three damage modalities (acoustic explosion, thermal burn, and mechanical disruption).

Typically, investigations of Q-switched laser exposure effects have typically concentrated on large foveal exposure areas at levels that always produced gross foveal damage (4). In such experiments long-term effects on visual acuity and spectral visual function have been reported (4,12). Total foveal damage results in acuity changes from 20/20 Snellen acuity to 20/200 Snellen acuity. It has been postulated that this initial acuity deficit results from the edematous process associated with such a severe retinal injury (4,13).

After several weeks such changes usually have been reduced to levels more consistent with expected foveal acuity loss, if only the central foveola was damaged. While the abatement of the edema may take several weeks, recovery of function continued over several months (4). The explanation of such recovery may reside in observations made by T'so (13), who found that gross morphological photic damage to the macula of the rhesus monkey abated over several months post-exposure. Animals sacrificed at six months post-exposure showed near normal foveal macular areas as compared to animals sacrificed earlier. T'so (13) suggested that in the course of post-exposure recovery, photoreceptors adjacent to damaged photoreceptors slide into areas originally occupied by the damaged receptors, filling in the foveal retinal receptor mosaic. This finding may explain how overall acuity can recover while spectral sensitivity for the fovea remains altered (12); new cones may provide the resolution mosaic necessary for acuity

but, because of different absorption spectra, they alter the overall spectral sensitivity of the fovea itself.

Several recent experiments (4,14) have suggested that acute exposures can have non-thermal components, especially at energy levels determined for the transition zone from temporary to permanent visual function change. It is possible that such foveal retinal damage mechanisms could not be elucidated in studies similar to those mentioned above, where the entire foveal region has undergone gross damage. Furthermore, in most of the investigations where suprathreshold exposures were made, the exposures were placed when the animal was under anesthesia. Thus, examining the immediate transient alteration of visual function was impossible. Measurements were only obtainable two to three days post-exposure when the animal could respond.

Small spot, Q-switched, repetitively pulsed laser exposures represent a realistic hazard. Such exposure can occur with present day laser systems, either in training or in combat. The immediate effects of such exposure on vision are not resolved. In the present experiment, we have sought to examine the effects of small spot laser exposures that were placed on the fovea by behavioral procedures. We have studied the rhesus contrast sensitivity function to determine how such exposures might alter spatial visual function for both transient and long-term observations.

METHOD

The optical system used in this experiment is shown in Figure 1. The raw beam from a frequency doubled neodymium laser source (532 nm) operating at 20 HZ was made coaxial with the gap in a Landolt ring acuity target subtending 1 min of arc (20/20 Snellen acuity). Exposure during a session consisted of one to three bursts of six 20 nsec pulses delivered within a 300 msec time window. The nominal total intraocular energy (TIE) per pulse for a 3 mm pupil, averaged 1-3 microjoules This energy level is within the threshold region for producing minimal ophthalmoscopically visible retinal burns. Due to the parallel nature of the beam, exposure resulted in diffraction-limited retinal spots (20-50 microns).

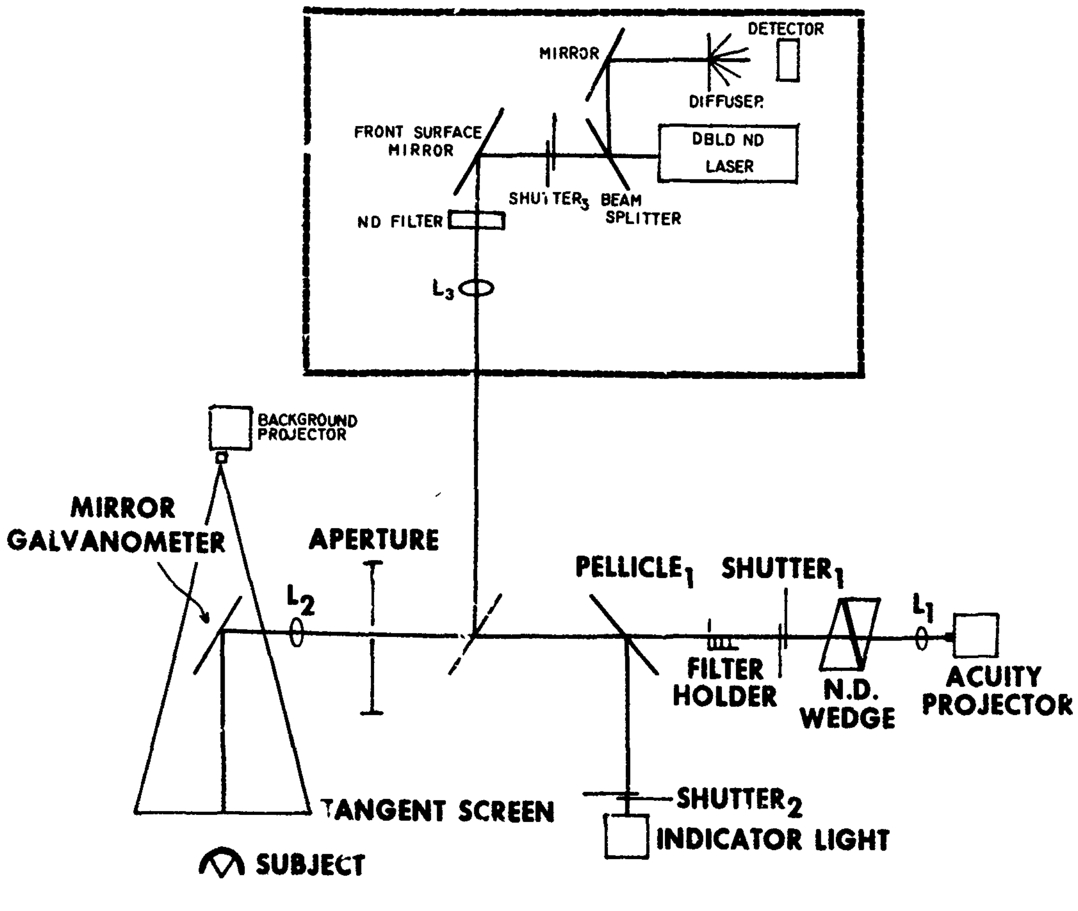

Figure 1. Alterations in contrast sensitivity were examined following exposures to a Q-switched frequency-doubled neodymium laser (532 nm) operated at a 20 Hertz pulse repetition frequency. The optical design allowed for placement of the laser beam coaxial with a 0.75 min arc gap in a Landolt ring, producing diffraction-limited (50 micron) retinal exposures.

Landolt rings and rings without gaps were projected onto a ground glass rear projection screen located about 0.5 meters directly in front of the rhesus monkey. All of the stimuli were negative contrast achromatic (white figure on a dark background) targets so that an independent light source could serve as a background contrast channel. Because the luminance of the background channel was additive with the target luminance, the contrast ratio was defined as the luminance of the test plus the background, minus the background, divided by the sum of the luminance of the test plus two times the background. Contrast sensitivity was defined as the reciprocal of the contrast ratio required at threshold for accurate discrimination of the acuity stimuli. The gap size of the Landolt rings varied from 0.7 to 14 min of arc. This range of visual angle is equivalent to spatial frequencies from 38.5 cycles/deg to 2.2 cycles per degree.

Four rhesus monkeys (Macaca mulatta) were trained on a Landolt ring visual acuity task (12,14,15) in which exposure to a laser flash could be administered during task performance (4,14). Training required 6 to 9 months for each animal to discriminate Landolt rings from gapless rings successfully, and several additional months for stable threshold acuity measurements in each animal. Briefly, this behavioral procedure required that a response lever be depressed and held down by the animal for a variable period of about 3 seconds following the presentation of a small white spot of light. The acuity target (either a Landolt ring or a gapless ring) would then be presented for 500 msec on the rear-projection tangent screen facing the animal. If the animal released the response level only following the offset of the acuity target, two additional response panels were illuminated, displaying a Landolt ring and and a gapless ring. Positive reinforcement (fruit juice) required that the animal depress the correct panel, matching the stimulus target presented. Correct delayed forced choice matching responses caused subsequent targets to be presented at reduced contrast levels, while incorrect responses resulted in increased target contrast on the next trial. Target contrast was controlled by the use of circular neutral density wedges. All animals had pretraining refractive errors of less than 1/2 diopter; all had normal-appearing retinal fundi prior to exposure. Reexamination of any given animal's retina was generally given after all of its exposures had been completed.

Contrast sensitivity for Landolt ring test stimuli was determined by an up-and-down visual tracking procedure (4,12,14,15), allowing rapid determination of threshold. Animals were trained to yield highly stable baselines with minimal variation across sessions. A stability criterion of approximately 0.2 to 0.4 log units in contrast, maintained over a 30 to 60-minute period for several sessions was generally required before the animal was placed in the exposure paradigm. The effect of binocular laser exposure on contrast sensitivity was determined for one spatial frequency each session, as long as post-exposure measurements on the tested spatial frequency returned to its previously determined session baseline levels. Contrast sensitivity measurements over the entire spatial frequency spectrum were made periodically between exposure sessions to determine long-term changes not observable in the daily exposure sessions.

RESULTS

Recovery of contrast sensitivity following laser exposure for a large target (20/267 or 2.2 cycles/ degree) and a small target (20/15 or 38.5 cycles/deg) is shown in Figure 2. The ordinate represents the percent deficit of postexposure sensitivity relative to the sessions baseline sensitivity before exposure. Sensitivity averaged over 2 - minute blocks following exposure shows similar transient changes for large and small targets, both in maximum deficit and time course of recovery to baseline. Figure 2 shows recovery functions for a single animal, however the results are representative of the transient deficits observed for all subjects.

Data derived from recovery curves (Figure 2) for each of the four animals show that recovery time is nearly uniform across the spatial frequency spectrum. Mean contrast sensitivity at 2,6, and 16 minutes post-exposure, across all exposure sessions for each spatial frequency, is shown in Figure 3. For each of the four animals, the decrease in contrast sensitivity appears to be uniform across spatial frequencies. Both small and large targets showed little recovery during the first 2 to 4 minutes postexposure. After the initial 4 minutes postexposure, recovery was evident, with return to baseline by 16 minutes.

Repeated exposure trials had no initially observable long-term effects on contrast sensitivity. However, after several months differences in the slopes of the post-exposure contrast sensitivity functions became evident (Figure 4) for three of the four animals tested. The change in slope was a steepening due to an increase in the contrast sensitivity for the larger spatial frequencies, while sensitivity for the finer frequencies showed minimal change. In one of these animals (S3), exposure was continued until contrast sensitivity was no longer obtainable at the finest spatial frequency. Full spectrum sensitivity measured after this loss of foveal function (Figure 5) revealed a more shallow slope for the contrast sensitivity curve, approximating that of the preexposure function. Coincident with the loss of fine spatial frequency sensitivity there was a return to preexposure level for sensitivity measured for the largest spatial frequency targets.

Fundus observations of animals examined after the completion of all laser exposure sessions revealed small punctate lesions in the foveal areas including the foveola. A representative fundus photograph of such a retina is shown in Figure 6.

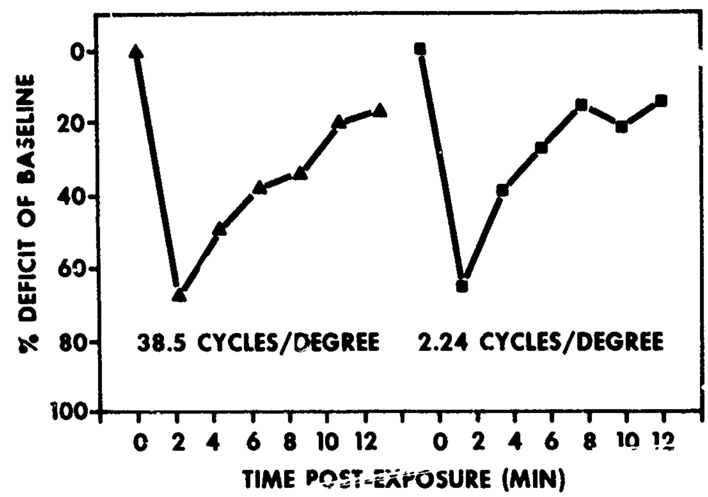

Figure 2. Sample recovery of contrast sensitivity following laser exposure. Contrast sensitivity measured for a large target (2.24 cycles/degree) and a small target (38.5 cycles/degree) is plotted as the percent deficit of post-exposure sensitivity relative to that session's preexposure baseline. Sensitivity following exposure shows similar transient changes both in maximum deficit and the time course of recovery to baseline.

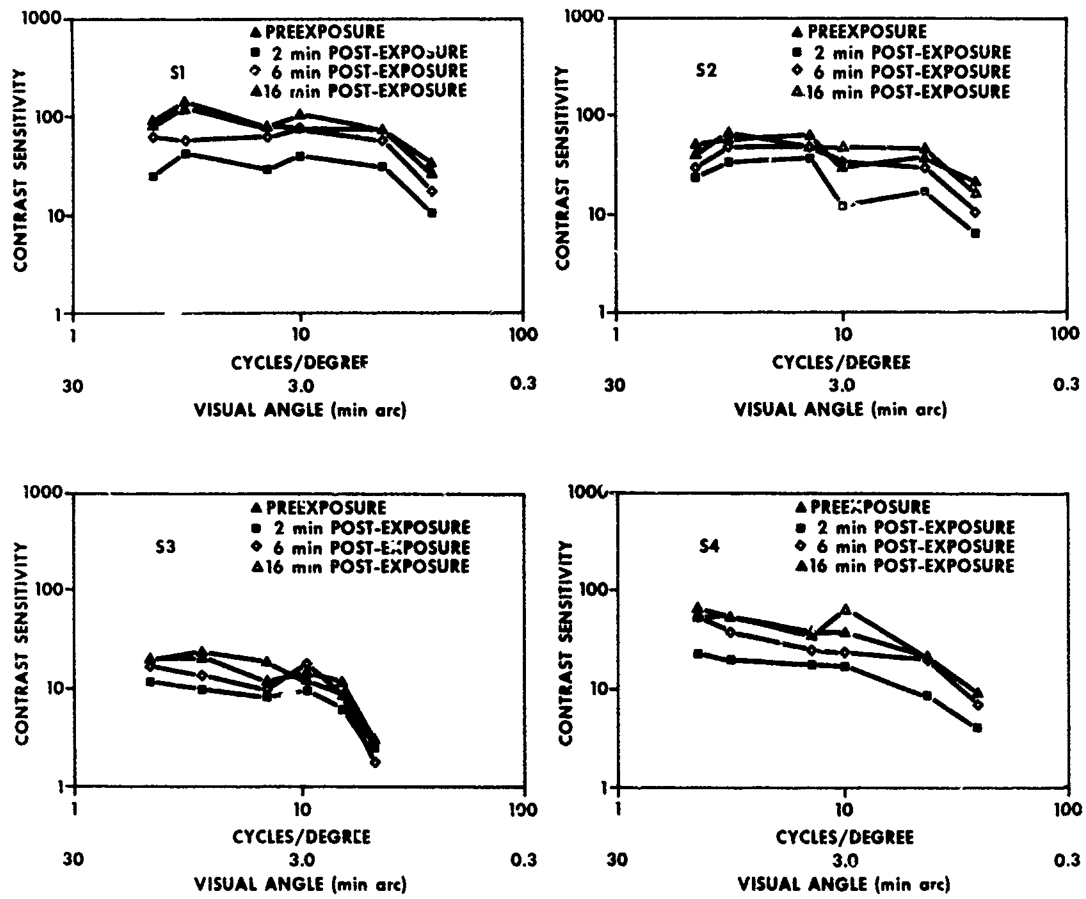

Figure 3. Data derived from recovery curves was used to examine the transient effects of laser exposure across the spatial frequency spectrum from 2.24 to 38.5 cycles/degree. This frequency range corresponds to an angular subtense of 0.75 to 14 min arc for the gap in the Landolt ring targets. For all animals, contrast sensitivity over the first 2 minutes following exposure was uniformly depressed across the spatial frequency spectrum. While full recovery was evident in most cases by 16 minutes, recovery for the mid-range spatial frequencies appeared to be more rapid than that observed for the low and high spatial frequency targets.

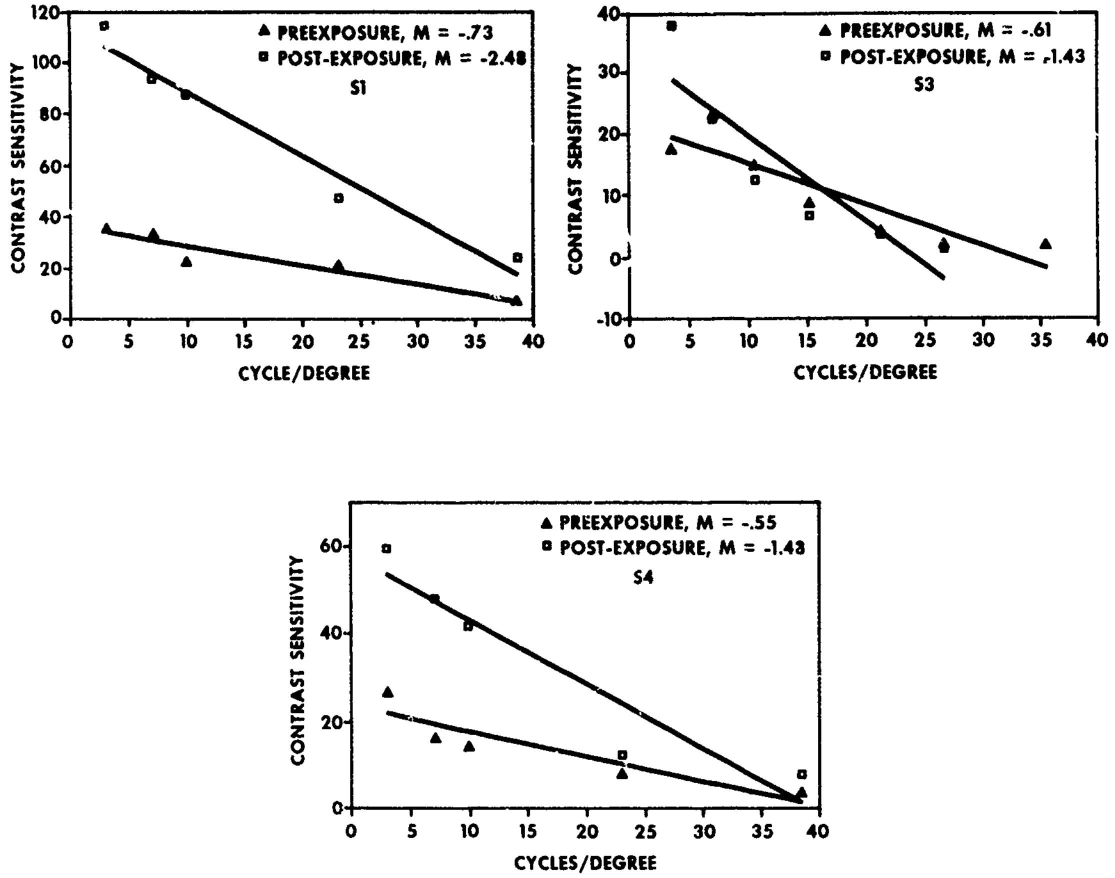

Figure 4. Long-term effects of small spot lesions were not readily apparent following daily exposures. Recovery to preexposure contrast sensitivity usually occurred within the same session. Examination of the full spectrum contrast sensitivity function after cumulative exposure sessions, compared to similar functions obtained prior to any exposures, revealed a steepening in the slope of the post-exposure function, as determined by a linear regression using the Least Squares Fit method. This steepening involved an increase in contrast sensitivity for the lower spatial frequencies with minimal change for the finer test targets.

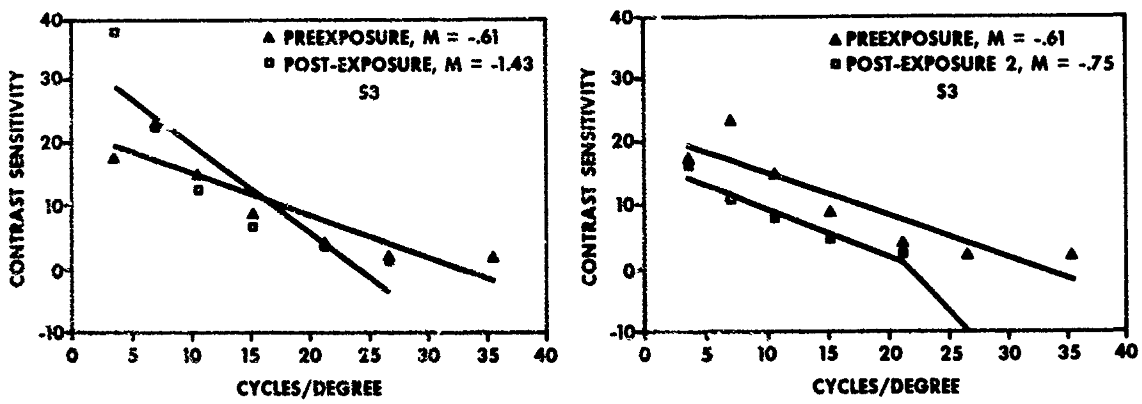

Figure 5. Cumulative foveal exposure was continued for one animal (S3) until a permanent high frequency loss was evidenced by the inability to obtain contrast thresholds for the smaller acuity targets. When this deficit occurred, sensitivity for the low spatial frequency targets returned to normal levels. A slightly steeper slope (-0.75) for the post-exposure 2 function results from the decrease in high frequency contrast sensitivity.

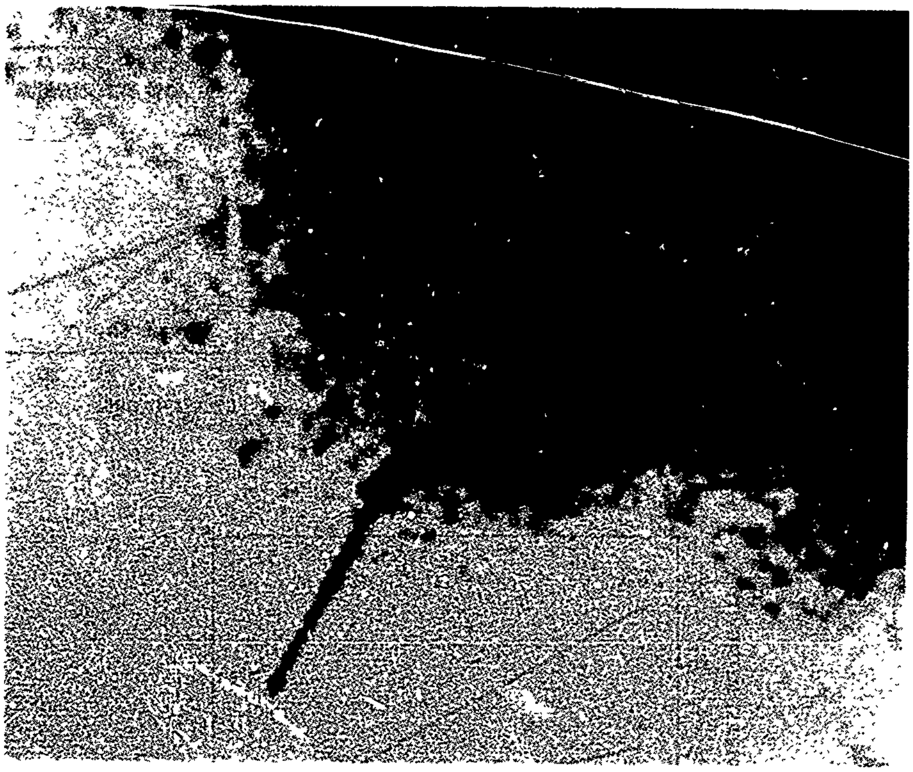

Figure 6. Fundus observations of animals examined after the completion of all laser exposures revealed small punctate lesions in the foveal region, including the foveola. The fundus photograph above, taken from one of the animals, shows the central pattern of lesions consistent in size with minimal spot retinal exposures.

DISCUSSION

The transient changes in sensitivity obtained for exposure conditions used in this experiment differ considerably from those obtained in experiments where foveal damage was more complete or where exposure duration was considerably longer (100 msec). In experiments where foveal damage was more complete, long-term changes in achromatic acuity were measurable as long as six to nine months post-exposure, and where acuity recovery had been obtained, spectral acuity and sensitivity measurements still revealed a basic change in foveal function (10). In investigations where longer pulse widths (100 msec) and spot sizes from 50 to 350 microns were used, a transition level between permanent visual change and transient visual change was typically found, although smaller spot exposures did require higher transition level exposure energies (4).

More than one experimental factor may be responsible for the present results. The current experiment dealt with irradiation spot sizes of about 50 microns compared to spot sizes varying between 500 and 1000 microns used in previous Q-switched exposure experiments of the present type. The transient effects observed here may reflect similar damage processes observed with larger spot size exposures, but related to a more limited area of foveal damage. Transient recovery functions might reflect the spread of local edema from the exposure site and the subsequent reduction in its local opacity.

Following such possible edema abatement, a sufficient number of foveal photoreceptors may initially still be available to mediate normal spatial vision processes, even though photoreceptor damage has occurred. With continued exposure, as was the case here, a sufficient number of foveal photoreceptors may eventually become damaged producing the observed alteration in the slope of the contrast sensitivity function. The elevation in sensitivity for the larger gap sizes may reflect foveal cone damage manifested by a disinhibition of the normal lateral inhibitory influence of foveal cones on parafoveal receptor systems; alternatively it may reflect more parafoveal involvement in the contrast sensitivity measurement as foveal photoreceptors are gradually damaged. As exposure continues, more spatially spread out damage may produce a permanent reduction in sensitivity, generalized over much of the spatial frequency spectrum. Furthermore, fine tuning of the retinal mosaic by local receptor alignment adjustments might serve as the mechanism for masking initial loss in fine acuity (16,17). Morphological evidence for such mechanisms has been reported for rodent and primate photoreceptors (18,19,20,21).

The wavelength of the laser source (532 nm) is another factor that differs from previous experiments using Q-switched exposures. All previous experiments involved laser wavelengths either in the near infrared (1060nm) or long wavelength region (694 nm). The

wavelength used in the present experiment is very close to the peak of the photopic sensitivity function (550 nm) and uniquely situated with respect to the absorption maxima of the two long wavelength cone pigments (520 and 575 nm). Thus, efficiency of such Q-switched exposure to alter visual processes either transiently or permanently should not be overlooked. While edema may contribute to the short-term change in function, photochemical damage processes found in many other experiments may account for the longer term changes in contrast sensitivity. Even transient changes may result from cone photoreception of 532 nm quanta, inducing neural spread due to receptor overload. The failure to observe more obvious permanent change may simply reflect our use of achromatic acuity targets. In experiments supporting photochemical photoreceptor damage mechanisms, spectral test stimuli were always used (4,6,10). Spectral test stimuli show that more permanent effects are either revealed or reflected earlier for such measures of visual function (4).

Finally, the pulse specifications for this experiment differed from previous experiments. In this experiment Q-switched pulses were delivered in a pulse train. While no previous functional work has been done with Q-switched pulse trains of visible light, morphological investigations (22,23) involving threshold determinations for retinal burn suggest that such thresholds are lower than those obtained with single Q-switched pulses. Such pulse additivity might also contribute to the transient effect, as early work in our laboratory with single Q-switched pulse exposure often produced effects that were delayed up to 60 seconds. More recent electrophysiological work (24) confirms these findings. A single minimal spot Q-switched pulse may be capable of producing retinal damage, but still may be insufficient in signalling the initial visual event involved in quantal absorption by the photoreceptor chromophore. But when Q-switched pulses are presented together in a train of pulses lasting several hundred milliseconds, the visual event may be appropriately signaled to the neural retina.

Thus, while gross foveal damage from large spot, Q-switched laser sources would provide an obvious clinical signal that vision has been altered, small-spot exposure might not provide as obvious a signal. Furthermore, as many present military rangefinders and designators involve non-visible wavelengths, retinal damage could occur without any obvious change in vision.

Novel military clinical visual function tests may be required for detection of retinal injury. Measures of visual acuity, alone, would not show the inhibitory/disinhibitory nature of retinal alteration as seen by the slope changes in contrast sensitivity reported in the present experiment. Conventional sine wave grating contrast sensitivity measurements may also be insufficient, as they are designed to treat the retinal surface as a detector with uniform sensitivity. Clinical tests that measure both spectral and spatial resolution under threshold contrast conditions represent the most sensitive kinds of visual function tests capable of early preventive diagnosis. As training and combat requirements involve ever-increasing usage of directed energy devices, the development and evolution of appropriate visual function tests must be given the highest priority.

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In conducting the research described in this report, the investigation adhered to the "Guide for the Care and Use of Laboratory Animals," as promulgated by the Committee on Revision of the Guide for Laboratory Animal Facilities and Care, Institute of Laboratory Animal Resources, National Research Council.

DISCUSSION
Papers 18 and 24

24. Dr Zwick - US - Permanent Visual Change Associated with Punctate Foveal Lesions.
18. Dr Farrer - US - Eye Protection Against Intense Light Sources.

Punt NE: A question concerning the relation of the exposure time to the anatomy of the retina. Is it not possible to obtain more information by means of fluorescein angiographic methods because the electro physiological methods only give results of the total system and I think not enough concerning the details of the retina?

Farrer US: Yes, we have made fluorescein angiograms and documented the events which you describe. Keep in mind that the fovea centralis has no vascular supply, so the lesion has to be very dramatic and penetrate the entire thickness of the retina to produce injury at the substrate layers in order to get a haemorrhagic lesion in the foveal region. The events about which we speak, are to the biologist, instantaneous. The decrement that we see from these large lesions is for practical purposes also instantaneous. I realise that the physics community make a dramatic issue of the time lags that can be in nanoseconds or microseconds and this is an event that I neglected to mention in looking at the plexiglass materials. One of the hopes for eye protection, one of the hopes for enhanced materials, is the ability to be able to capitalise on the fact that there is a delay, however minute, between the deposition of energy on the canopy and the re-radiation event which we saw as the plasma re-radiation. It is, perhaps, possible to develop new materials for canopies which will exploit these delays and give us an opportunity for eye protection in that regard. To answer your question again, more succinctly, for practical purposes the visual function decrement that we see is instantaneous with these dramatic lesions caused by lasers well above the threshold level. If we did not see the decrements instantaneously, in the biological sense, then we have not seen them in rhesus monkey models. I have not seen delayed reactions.

Brennan UK: I think your point about fluorescein angiography is very good. When we used fluorescein angiography we found it was a much more sensitive technique for the detection of damage than ophthalmoscopy. It is not as sensitive as histology, but you have to remove the eye and section it for that, at least you can use fluorescein angiography in accident investigations. It really depends on the fact that the pigment epithelial cells have tight junctions (zonular occludens) between them, and when you heat up the pigment epithelium you pull apart these junctions so that you get percolation between the pigment epithelial cells from choroid to retina.

Price US: First, does the PLZT offer any protection against canopy flash that you know of?

Farrer US: Do you mean building a canopy out of it?

Price US: No, does wearing the PLZT protect against flash blindness from the canopy flash?

Farrer US: As the re-radiation is in the spectral range that the PLZT responds to, it would close as a result of the re-radiated light. The question, of course, is getting it to close rapidly enough to do the job, bearing in mind that the brightness of the re-radiated flash is material dependent. Some materials re-radiate more brightly than others. In general the re-radiation is not the dramatically brilliant event that direct exposure to the laser causes, the re-radiation causes flash blindness not a retinal burn phenomenon. Under daylight conditions you might only produce flash blindness lasting 2 or 3 seconds. Under night-time conditions however, you would impose a greater penalty, particularly with material that re-radiates very brightly, there we project a flash blindness lasting 60 to 90 seconds.

Price US: Yes, I understand that it is flash blindness rather than a retinal burn phenomenon but certainly in helicopter flight, 2 or 3 seconds becomes critical if you are in a compromising position. You mentioned that multiple pulse protection was academic against the second, third and fourth pulses if the energy through the PLZT were sufficient to close it. I was wondering why you made that statement?

Farrer US: It is a good question and I appreciate the opportunity to elaborate a little bit. If indeed the first pulse were of sufficient energy to produce a catastrophic amount of damage to the eyes, the mission could be lost and under practical conditions it could be fatal. Any additional damage to the eye would be academic and that is all I meant to imply. Keeping energy out of the eye is good, keeping as much out as possible is even better.

Price US: Concerning the temporary impairment that occurs after the initial insult with your animals. You showed the time of recovery was essentially a normal function, how much of the retina does that involve? In other words in a human, how much of the peripheral vision would that take out, how many degrees? I don't know if you would have any way of measuring that.

Zwick US: It is strictly limited to the foveal area in the rhesus, it is about 200 microns, you can see how the lesions are clumped, they are clustered in an area of about 100 microns in the central retina, it should not affect peripheral vision at all. It affects large target measured contrast sensitivity function but this is not the same as measuring visual fields.

Price US: Thinking back, I do recall now you showed that you may have 20/200 vision almost immediately after that injury.

Zwick US: No, the flash does affect a 20/200 target in the same manner as it affects a 20/10 target, in other words measuring the sensitivity of a large versus a small target.

Price US: I wonder if a pilot can fly immediately after exposure, I know if it takes a great deal of time to recover full foveal sensitivity and normal vision. I wonder how long after a microscopic insult it would take to recover sufficient visual acuity to fly an aircraft.

Zwick US: I do not know what the relationship is between sufficient visual acuity and the ability to fly an aircraft: it is not a small point, it is a major point.

VISUAL DIFFICULTIES ASSOCIATED WITH FUTURE WINDSCREEN AND HUD INTEGRATION

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SUMMARY

The integration of a binocular HUD and the windscreen requires the consideration of a number of optical parameters if the HUD symbology is to be superimposed on the real world scene without giving rise to unacceptable visual difficulties. This paper describes these parameters and the causes of these difficulties, and reports a number of experiments carried out during these investigations. The significance of these results for future aircraft and their operations is discussed.

INTRODUCTION

The impetus for this investigation was the report on a battle exercise in 1972, which stated as one of its principal conclusions that many of the pilots had not been satisfied with the visual performance of the weapon aiming facility provided by the binocular HUDs fitted to the aircraft. The problems seemed to be associated with the focussing of the target marker, but descriptions of the pilots' complaints were too vague for any definitive conclusions to be drawn. Consequently a working group was convened and an early action was to seek written descriptions from operational pilots of any unsatisfactory features of the binocular HUDs they were using. Replies were diffuse and inconclusive. The group finally made recommendations limiting the vergence angle tolerances on the binocular sightlines to the HUD sighting mark. However it was felt by the Company that a greater understanding of the mechanisms of the problem needed to be developed and described. Only then could pilots realistically be expected to comment on their occurrence. This paper summarises the results of this study and examines its impact with respect to future ground attack aircraft.

Binocular Vision

In order to be able to experience all the visual difficulties described here, one must possess both sustained binocular vision and sustained stereopsis. Sustained binocular vision in this text refers to the continuous functioning of both eyes and the ability to fuse the retinal images into one percept.

A simple test which the reader can perform to establish whether he has this faculty is to look at an object about 20 feet away with both eyes. Then raise a thumb into one's general direction of gaze, at about 1 foot away from the eyes.

While continuing to look at the object, the possessor of sustained binocular vision will also see two steadily sustained out of focus thumb outlines. He will be able to move these across his gaze by moving his hand until one outline lies on each side of the object, whereupon the two thumbs may each appear steadily or intermittently transparent.

The observer not possessing sustained binocular vision will see at the same time as the object only one thumb outline, which will always be steady and opaque, or he may see two thumb outlines intermittently. In this case one half of the visual system is more 'dominant' than the other, and this suppression is a sort of built in mechanism to prevent double imaging.

Stereopsis is the binocular visual perception of depth or distance. A majority of adults possess this faculty in some form, but it has become apparent that it has considerable variety of form amongst the population (Richards 1970 and 1971). It appears to be dependent upon feature content, relative brightness and colour contrast (Gregory 1979). Richards (1970) found in a survey of 150 people that 4% were unable to utilise stereoscopic vision cues at all, and that 10% had great difficulty with them.

Pilot applicants for the Royal Navy are expected to pass a stereopsis test, whilst Royal Air Force applicants are not. No record is available of how may Royal Navy applicants fail to discern the required standard of stereopsis.

It will be noted that the effects described herein, will be more obvious to those people with a high level of stereoscopic acuity.

Visual Difficulties

Three types of visual performance difficulties can arise when target sighting with a binocular HUD. These are:

i) binocular sighting confusion with ground targets
ii) double imaging (diplopia) with ground and air targets
iii) parallax shift between sighting mark and target images with ground and air targets.

Before explaining these phenomena in detail it may be useful to clarify some of the terminology which will be used, and then to consider the optical paths associated with a typical HUD installation.

We define the angle LTR in Figure 1 between the two sightlines LT and RT when steadily viewing point T binocularly as the binocular vergence angle (b.v.a.). We shall regard binocular vergence angle as being positive in sign when the sightlines converge as shown, as they do for object points being observed in nature.

Figure 2a illustrates a typical HUD installation. The light from a distant target can be regarded as parallel. If the windscreen and combiner were perfectly flat, the target light entering the cockpit and passing through the HUD combiner would remain parallel. The perceived position of the target would be the same as its actual position. If we now introduce the HUD, with a sighting marker collimated perfectly to infinity, the sighting mark light from the combiner would be parallel in each eye. Thus the target and marker images would be coincident in apparent range, and would be perceived by the brain as a single fused binocular image.

Diplopia and Parallax

If the HUD is adjusted by moving its CRT towards its projection lens, the sighting marker will have an apparent position much nearer than the target (see Figure 2b). An observer with good stereoscopic vision will then be able to discern two effects. First, if he fixes his attention on the target the marker will appear unequivocally double. Fixating on the marker will cause the target to appear double. This effect is known as binocular diplopia or more commonly just diplopia. The observer will find that he is able to overcome this double imaging by closing one eye at a time, but in doing so will notice a parallax shift between the sighting mark and the target.

Binocular Sighting Confusion

In Figure 2c the HUD CRT has been moved away from the projection lens (in order to demonstrate the third effect of binocular sighting confusion). If the observer now attempts to view the sighting mark it will appear beyond the target. It may be difficult to envisage a marker 'beyond infinity' but the optical geometry is such that the sightlines to the eyes have been made to diverge, i.e. there is a negative sighting mark b.v.a. When sighting a ground target the perceptual process seems to have difficulty reconciling the stereoscopic cues and the terrain feature cues. The result is either a blurring of the target or of the marker, and this is frequently accompanied by some form of unpleasant physical sensation.

This description goes some way to describing the visual difficulties which can occur with a decollimated HUD, but the issue is whether these effects are observed on aircraft, and if so what can be done to alleviate them.

Head-Up Display (HUD)

The modern binocular HUD has evolved initially in the UK, where the first Service installation was made in 1957. (The advantage of collimating sighting marks to infinity had been discovered and developed on the monocular reflector gunsights in the 1930s). One advantage of the binocular HUD is that by viewing both sighting mark and target binocularly the pilot gains the advantages of slightly higher sharpness of vision (binocular visual acuity being about 1.3 times as good as with only one eye) and gains some sureness of judgement and comfort resulting from sustained binocular vision.

In a perfectly collimated HUD projector, the light rays from the CRT would emerge from its combiner glass as a perfectly parallel beam. However some manufacturing tolerances are inevitable. HUD manufacturers use either the term 'binocular parallax' or the unqualified term 'parallax' to describe the HUD b.v.a. value. Tight control of the collimation quality receives close attention in both design and manufacture, and sales brochures for HUDs now claim to achieve binocular vergence angles of $\pm$ 0.5 mrad.

Early in our investigations it was suspected that the complaints recorded in the exercise in 1972 were due to the interfacing of the binocular HUD projector to the pilot's vision. Subsequently, an experimental projector was constructed (see Figure 3) based on an overhead viewgraph projector with a 3½" diameter lens and a HUD combiner glass. This enabled the binocular viewing of a HUD target marker with a variable HUD b.v.a., against a number of real world targets. Once calibrated, it enabled the adjustment of the sighting mark b.v.a. over $\pm$ 5 mrad in gradations of 0.1 mrad. Subjects for the first trials included three test pilots and eleven civilians who had been tested for stereopsis with the Titmus circles stereo test and had passed its 40 arcseconds stereo acuity test. The targets used included a house a mile away surrounded on all sides by a hillside background, as a ground target, and passing aircraft 1.5 miles away as air targets.

The investigation began by viewing the house target. Each subject slowly increased the b.v.d.a. angle (i.e. HUD b.v.a. - Windscreen b.v.a.). At a value of between +0.1 and +0.3 mrad subjects began to notice that the sighting mark appeared to be stereoscopically nearer to the observer than the house. This then indicated the stereo acuity threshold angle during sighting. Most subjects found it quite comfortable when the b.v.d.a. was just more than their stereo acuity threshold. As the b.v.d.a. was then increased, diplopia started to become apparent at approximately +1.0 mrad and was unmistakable at +3.0 mrad.

When repeated in the negative regime, a threshold value of between -0.1 mrad and -0.3 mrad was attained, at which the binocular appearance of the sighting mark remained single and clear, but that of the house within and around the sighting mark outline began to deteriorate in clarity in an uncertain and mystifying fashion. As this happened, subjects often reported unpleasant sensations in the eyes and even feelings of nausea. At b.v.d.a. values of beyond about -1.0 mrad, the typical observer found the effect so pronounced that the equipment could no longer be considered acceptable as a target sight.

As the equipment was adjusted towards -5.0 mrad, the unpleasant physical sensation intensified so much so that some subjects refused to continue looking through the combiner glass. It is believed that this binocular sighting confusion and discomfort result directly from the impossibility of reconciling the perceptual cues of stereoscopy and the overlapping contours. When repeated with the air target, if the b.v.d.a. was increased positively similar values for stereo acuity and diplopia were achieved. In the negative regime values were found to be symmetrical with those observed in the positive regimes. In this case it appears that the perceptual process is able to accept that the sighting marker's range is now beyond the target despite divergent sightlines to the sighting mark.

Further Investigations

In order to be able to demonstrate more conveniently the principal visual difficulties in binocular target sighting using portable equipment, a rear vision HUD demonstrator was developed (see Figure 4). This enabled the experimenter to reproduce the b.v.d.a.'s demonstrated on the viewgraph, i.e. reproducing identical values of retinal disparity angles. Five test pilots, all of whom had passed the Titmus stereo acuity test, were asked to find their limits of b.v.d.a. acceptability, in the positive and negative regimes. For an air-to-ground target a mean positive value of +2.26 mrad (SD 0.95) was attained and a negative value of -0.36 mrad (SD 0.41). Using an air-to-air target a positive value of +2.85 mrad (SD 2.2) and a negative value of -2.06 mrad (SD 1.53) were attained. Comparison of the air-to-air with air-to-ground negative b.v.d.a. values (-2.06 against -0.36 mrad) illustrates the importance of terrain features in causing binocular sighting confusion..

Insertion of a Windscreen

Following these investigations a flat laminated bullet-resistant windscreen was positioned in front of the projector at the appropriate installation angle and position. It was found that this particular windscreen altered by +1.3 mrad the b.v.a. value at which the sighting mark appeared to the observer to be coincident in range with a target. Whereas the real range of the target was 1.5 miles, its apparent range when viewed binocularly through the windscreen was therefore 158 feet. Our attention therefore turned to the optics of the windscreens.

Flat Windscreens

Present day UK Service aircraft fitted with binocular HUDs usually have flat windscreens. Weapon aiming requirements dictate that these should be of the highest optical quality. They are normally of laminated construction, comprising a core assembly of glass or plastic, the faces of which are covered with a thin abrasion-resistant facing. The essential adhesions are provided by relatively soft transparent interlayers of plastic sheets of such as polyvinyl butyrate. Minute variations in the uniformity of thickness of these 'interlayers' after lamination is completed, can be a source of undesired optical angular deviations.

An indication of the manufacturing precision required to minimise undesired optical angular deviations is given by the fact that a change of thickness of 0.00125 inch over a 1.25 inch windscreen span introduces a prism with 1 mrad apex angle and therefore close to 0.5 mrad optical angular deviation in all usual windscreen material combinations (since, deviation = (n-1) x apex angle, for shallow prisms, where n = mean refractive index). Thus, a central hump or hollow 0.00125 inch high in a 2.50 inch span will introduce respectively -1 mrad or +1 mrad binocular vergence angle (binocular deviation) between the left eye and the right eye. Such circumstances can readily occur in a windscreen of 1 or 2 inches total laminated thickness.

The optical angular deviation in an as-installed aircraft windscreen can be regarded as comprising a design component and an undesired manufacturing tolerance component. The manufacturing limits of binocular deviation required in current UK windscreen specifications vary from 8 arcminutes (± 2.3 mrad) to 10 arcminutes (± 2.9 mrad). The manufacturers sometimes claim that they are achieving binocular deviation limits which are considerably smaller than these maxima. Since records of these values for individual windscreens are not kept, it was decided that a number of windscreens should be evaluated.

One examination showed that 25 out of 30 windscreens acted as cylindrical convex lenses and attained actual b.v.a. values in the critical aiming area of the order of -1.5 ± 0.3 mrad. Assuming a HUD b.v.a. of ± 0.5 mrad a typical HUD/windscreen installation could be expected to have a b.v.d.a. of between +0.7 to +2.3 mrad; thus

(HUD b.v.a.) — (Windscreen b.v.a.) = binocular vergence difference angle (b.v.d.a.)

$$(0 \pm 0.5) - (-1.5 \pm 0.3) = +1.5 \pm 0.8 = \underline{+0.7 \text{ to } +2.3 \text{ mrad}}$$

Comparing this with the values obtained using the experimental viewgraph projector, it can be seen that the higher values would establish steady diplopia or parallax, whilst lower values would enable comfortable target sighting.

Three windscreens acted approximately as cylindrical concave lenses with a maximum b.v.a. in the same area of +1.2 ± 0.3 mrad. Again assuming a HUD b.v.a. of ± 0.5 mrad, the b.v.d.a. for this HUD/windscreen installation would be -2.0 mrad to -0.4 mrad; thus

$$0 \pm 0.5 - (1.2 \pm 0.3) = -1.2 \pm 0.8 = \underline{-2.0 \text{ mrad to } -0.4 \text{ mrad}}$$

Hence binocular sighting confusion against ground targets could be expected to occur with the combination of a HUD with any of these three windscreens. Two other windscreens were approximately non-deviating.

Implications

If we assume that the spread of b.v.d.a. values for the HUD/windscreen installations quoted overleaf, -2.0 mrad to +2.3 mrad, are of the same order as those present in Service aircraft, then we would expect the visual difficulties described to occur in some of those aircraft. It was stated earlier that pilots could not be expected to comment upon the occurrence of these difficulties unless they understood the mechanisms involved. To this end, the near vision demonstrator was used to explain to about 15 pilots how the phenomena of diplopia, parallax and binocular sighting confusion could occur. They were then asked whether they had experienced these effects during the last ten years or so. All had observed the phenomena to some degree, whilst many cited one or two aircraft in which either diplopia or binocular sighting confusion had been very pronounced. In these cases they had been assuming that they were having to deal with 'a bad HUD'.

It is now believed that these problems were likely to have been caused by an optical mismatch between HUD and windscreen. For this reason it is believed that HUD and windscreen b.v.a. limits should be such that the combined b.v.d.a. is kept between -0.3 mrad and +1.0 mrad, preferably lying just in the positive regime.

Future Aircraft

A current trend in aircraft design is the fitting of curved windscreens. The absence of windscreen pillars provides the pilot with improved forward vision. Some improvement in the aerodynamics can be another benefit. These aircraft will be expected to have a night attack capability. To achieve this the aircraft will be fitted with forward looking infra red (FLIR) sensors and, associated with these, wide angle field of view (WFOV) HUDs.

Curved windscreens are typically of uniform thickness and are made from single sheets of materials such as polycarbonate. The design shape makes its optical deviation performance close to that of a cylindrical concave lens, always diverging distant target light rays, i.e. having a positive design component of b.v.a. (binocular deviation). The b.v.a. of a wrap-around windscreen is directly proportional to its thickness and inversely proportional to the square of the local radius of curvature. A typical value would be about +2mrad for a 1 inch thick windscreen. Clearly the HUD b.v.a. will need to be set up so as to match the design b.v.a. of a particular type of windscreen.

Two types of WFOV HUDs are currently being manufactured, a dual combiner refractive HUD and a holographic or diffractive HUD. Figure 5 shows the respective binocular fields of view of these two devices. It will be noted that there has been an enlargement of the binocular field of view in both types which will affect the visual performance during daylight operations.

Following the introduction of the diffractive LANTIRN HUD onto the F-16 with its double curvature windscreen, Genco (1983) reported that pilots complained about double and blurred images when sighting upon a target. After a detailed investigation into the causes of these problems he recommended that to prevent diplopia, the windscreen and HUD must be considered as one system with a b.v.d.a. of no more than $\pm$ 1 mrad, the onus ultimately lying with the windscreen manufacturer to improve and control the optical quality of his product. However, doubts have been expressed by manufacturers as to whether, with current technology, it is possible to achieve these standards. It has been suggested that an adjustment of the HUD collimation should be available so that each HUD can be optically matched to its windscreen during installation,but this contradicts the operational requirement that as Line Replaceable Units (LRU), the HUD and windscreen should be replaceable independently and not require any adjustment during installation. Thus, one's attention shifts back to the optical quality of the windscreen.

Before this can be evaluated properly, new test procedures need to be adopted. Current test specifications for curved windscreens in the UK and in the USA call only for the measurement of absolute optical angular deviation and not the binocular angular deviation. It is important that the latter be measured accurately, so that at least the as manufactured b.v.a. of the windscreens be known. With appropriate information on the consistency of manufacture in the critical area of the windscreen, steps can be taken to determine what the allowable tolerances for HUDs and windscreens should be in order to achieve b.v.d.a. limits lying between about -0.3 mrad and +1.0 mrad.

Future Work

The requirement for a night attack capability will involve the use of night vision goggles (NVGs) with the FLIR. It was initially felt that the occurrence of these visual difficulties whilst using NVGs should be investigated. However, it soon became apparent that the stereo acuity of binocular NVGs was so poor that not only could the effects not be observed on the focusable HUD rig, but stereoscopic depth perception itself was practically impossible. In fact the acuity of the goggles is the limiting factor, this being in the order of between 2 to 4 minutes of arc compared to 1 minute or much less for the human eye.

The manner in which this will affect the pilot's capabilities has not yet been ascertained. However, current lines of investigation in this area include:

- the effect of limited depth perception on the basic flying task
- the effect of a reduction in stereo acuity on weapon aiming
- the decollimating effect of the windscreen upon the FLIR image when viewed through NVGs.

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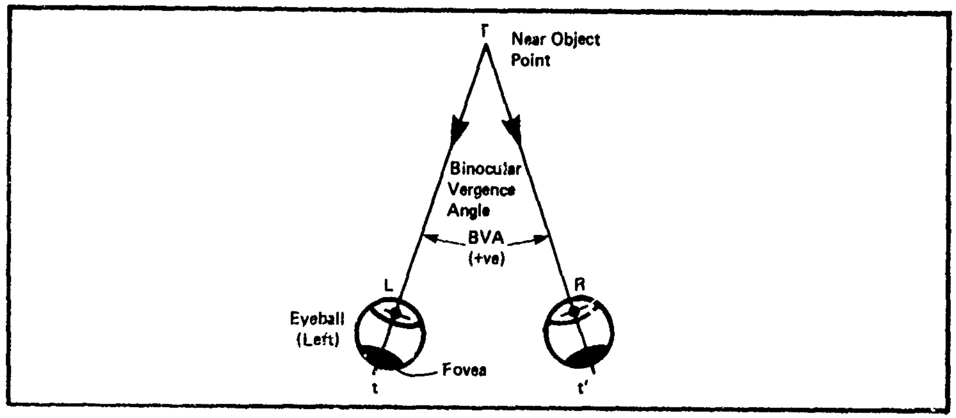

Fig 1. FUSED BINOCULAR VISION OF AN OBJECT POINT

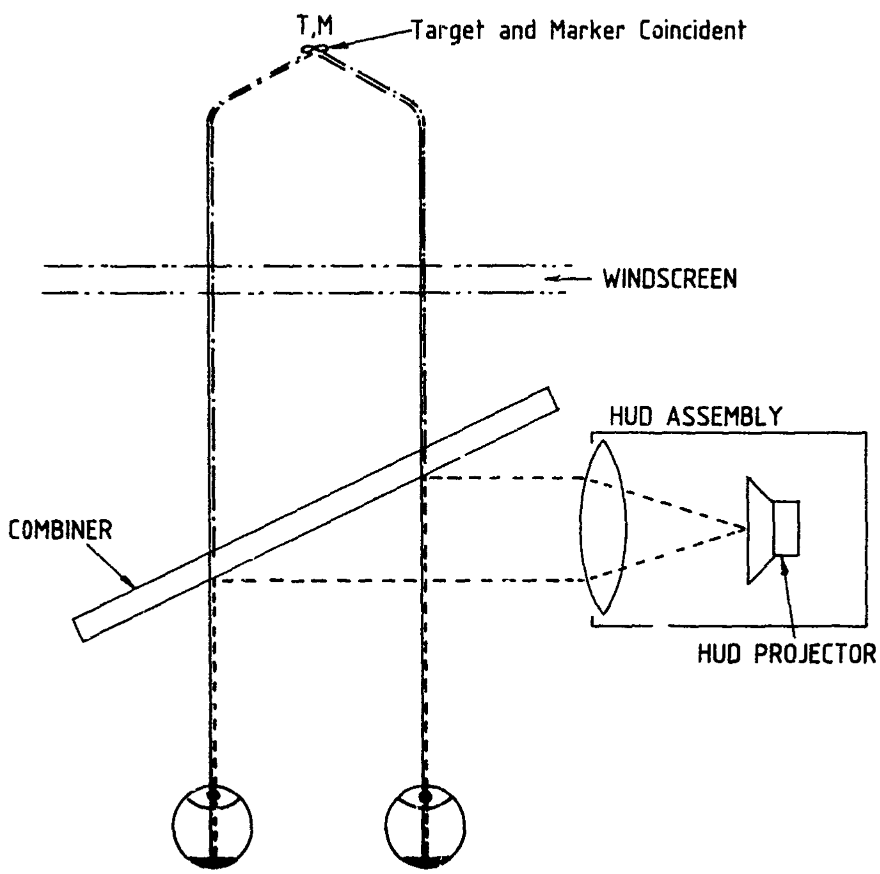

Fig 2a. TYPICAL HUD INSTALLATION

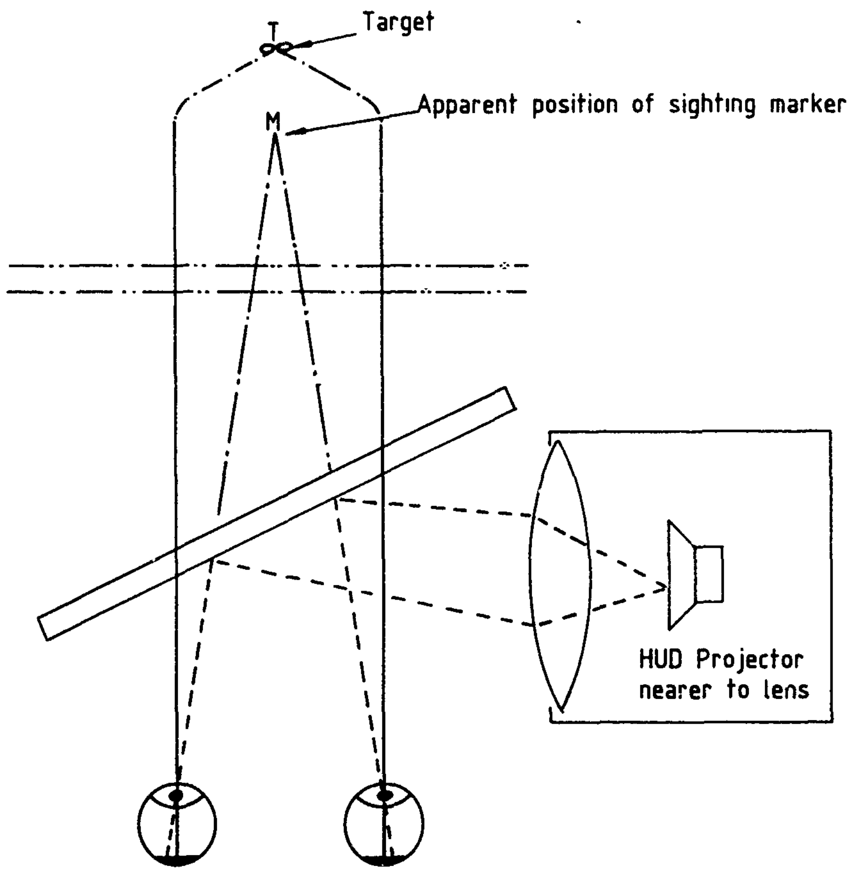

Fig 2b. HUD INSTALLATION-DIPLOPIA AND PARALLAX

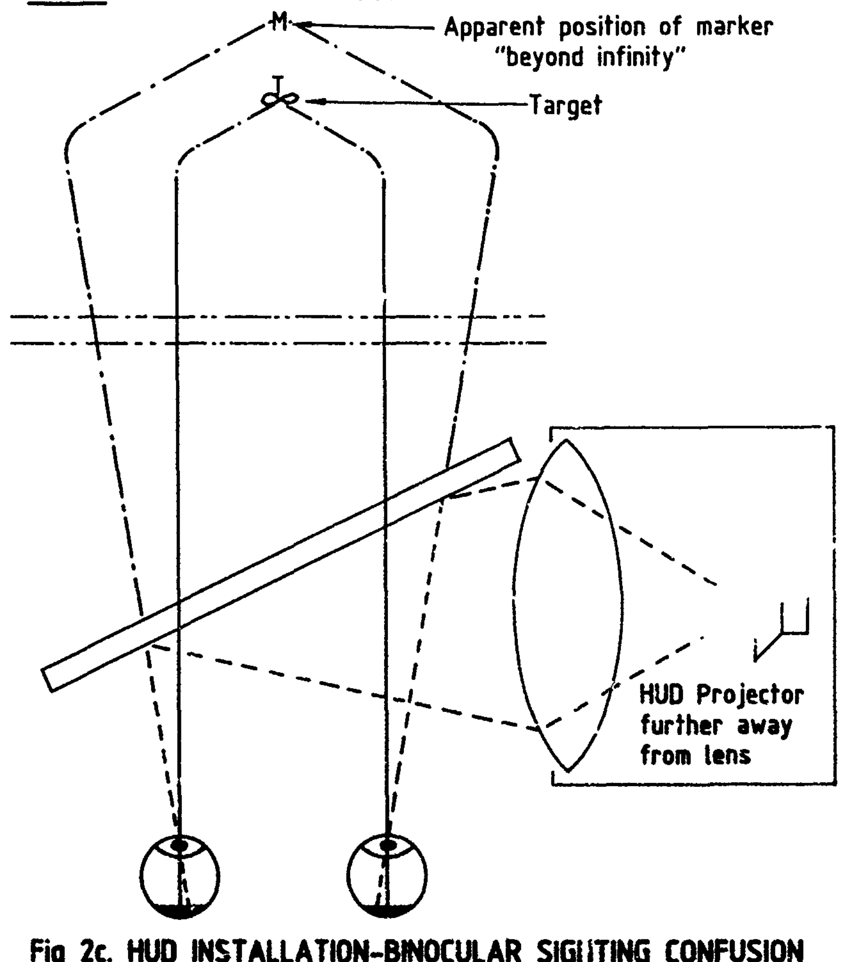

Fig 2c. HUD INSTALLATION-BINOCULAR SIGHTING CONFUSION

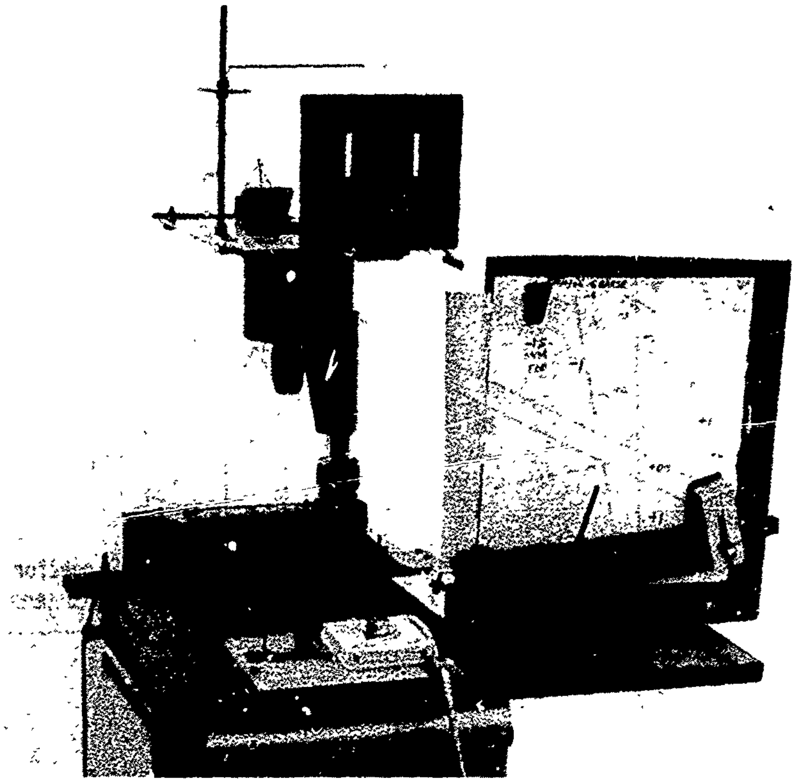

Fig 3. FOCUSSABLE VIEWGRAPH HUD PROJECTOR

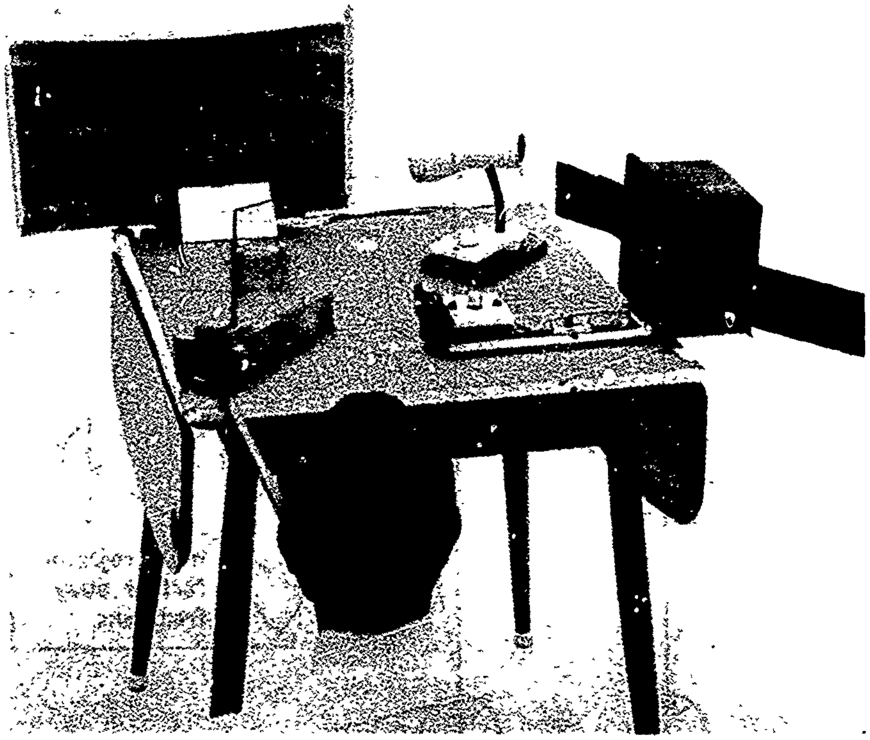

Fig 4. NEAR VISION HUD DEMONSTRATOR

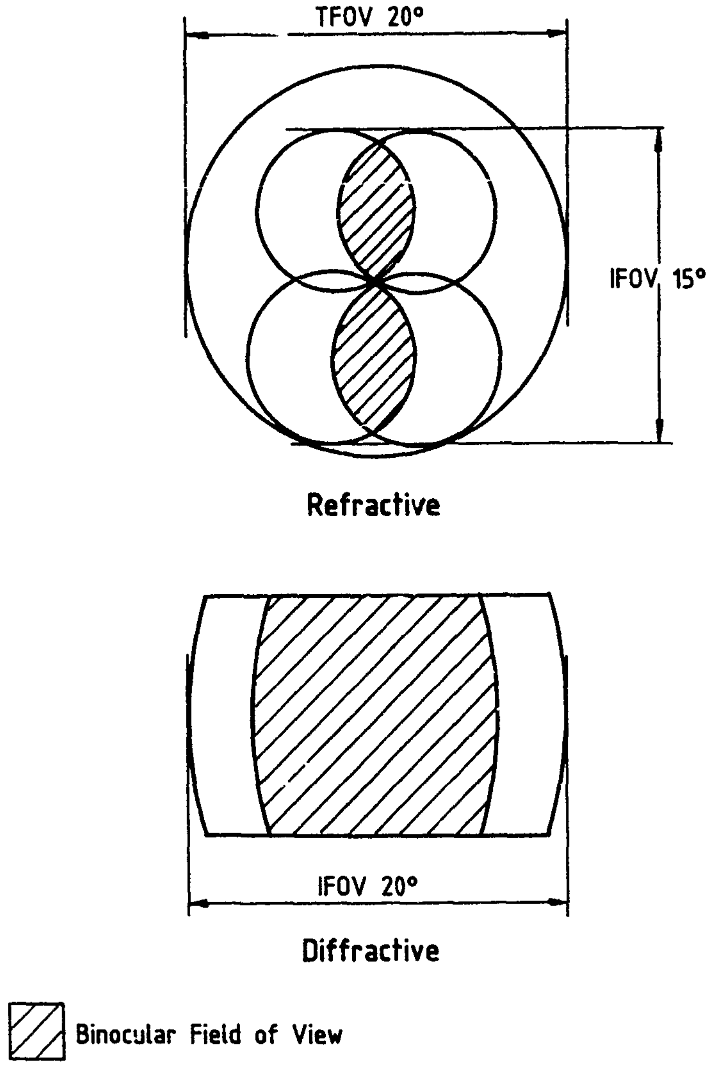

Fig 5. Typical Binocular Fields of View of Wide Angled HUD's.

HUMAN FACTORS

THE CINDERELLA DISCIPLINE IN COCKPIT INTERFACE DESIGN

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SUMMARY

The present trend in military aircraft design towards compact cockpits, multifunction controls and displays, and integrated systems within more agile and smaller airframes, has resulted a greater need for Human Factors involvement in the design of the man-machine interface. The cockpit of the modern military aircraft is inevitably a compromise of conflicting design disciplines, and one in which Human Factors fails to achieve any long term influence because the discipline lacks the "absolute" argument necessary for survival in the industrial environment. If Human factors are to establish the degree of influence the current levels of research justify, then a new approach is necessary. This approach must recognize the practical problems associated with the design and manufacture of the "integrated weapons delivery system", that future aircraft represent. One possible approach may be the generation of "Human Factors Design Tools", for use by engineers, which incorporate human sensory emulations and provide outputs that can be integrated into the engineering discipline.

INTRODUCTION.

All good fairy stories begin with "Once upon a time ...." and end with ".... and they all lived happily ever after." This is no fairy story and there is no Fairy God Mother to wave her magic wand and transform our Cinderella into a princess.

In principle the cockpit of the modern military aircraft is the culminated effect of conflicting design disciplines, balanced to produce a work station having a man machine interface performance which, although a compromise, represents the best obtainable within the limits of opposing requirements. Four major influences are involved: Engineering Design. Operational Capability, Human Factors and Finance.

At the conceptual stage of an aircraft project, when the arguments are nebulous, the Human Factors discipline is able to influence the cockpit design. Follow the project through development, production and finally to "in-service" operation and the Human Factor consideration has declined to "if the crew will fly it, buy it". Like Cinderella in reverse, Human Factors starts as an influential princess but ends up as the kitchen maid tolerated but ignored.

In this paper the authors will examine :-

1. Why Human Factors is failing to achieve a long term influence on cockpit design.

2. What effect that failure has on the overall performance of the aircraft.

3. What changes in the Human Factors approach are necessary to reverse the situation

spectral light in rhesus monkeys. Science, 174(1971), pp520-523.

4. One example of a new approach where a "Human Factors Mathematical Model" has found engineering approval and is influencing cockpit design.

AIRCRAFT MANUFACTURERS ROLE.

Prior to the current generation of military aircraft, the U.K. aircraft manufacturer was performing an airframe design and construction task for a customer who defined the engine design, weapon systems package and much of the avionics fit. Although responsible for the provision of a cockpit within the airframe, the general layout of that cockpit and the allocation of space / interfaces for the customer furnished equipment, the manufacturer had little say in the design and manufacture of the individual items or that of the man machine interface performance as a whole. The majority of the display and control equipment in the cockpit was dedicated to specific systems, with the design, manufacture and evaluation being carried out in isolation; indeed some systems were fitted after delivery of the completed aircraft. The evaluation of a complete interface occurred late in the aircraft development programme and its performance, as an integral part of the aircraft's operational capability, was in general the responsibility of the customer and not the airframe manufacturer.

The increased performance of current aircraft and new proposals for more complex weapons delivery packages, within smaller and more agile airframes, has led to a need for an integrated systems design approach with data transmission buses and multifunction display suites taking the place of the multiple dedicated systems. One result of this integration, is an increase in responsibility for the manufacturer in the overall performance of the aircraft as a complete weapons delivery system and with it responsibility for the man machine interface performance as an integral part of the whole.

The military aircraft construction business has always been competitive and one which naturally adapts to technology changes. However, the rate of technology change continues to increase with time and consequently so does the cost of research and development. The level of investment currently tied up in a given aircraft project is so high that the pressure to build to a price, in the minimum of development time but incorporating the most advanced technology possible, dominates proposed designs and makes compromise a more critical part of the design task.

HUMAN FACTORS IN INDUSTRY.

Traditionally the design of the cockpit was seen as an engineering task with aircrew providing the necessary human factors and operational inputs. This evolutionary process where the engineer produced the hardware and a selected number of aircrew subjectively commented on the ability of the system to fulfill its task, was valid when the systems were simplistic and the interface relatively uncluttered. As the system complexity increased and the interface performance became more critical to the overall operational performance of the aircraft, a "love hate" relationship could develope between engineers and aircrew, where engineers criticized aircrew for not making up their minds and crews criticized engineers for never fulfilling their promises. The result was a generation of aircraft with cockpits which, if judged by present design criteria, might be considered as "ergonomic slums", where the lack of human factors involvement in the cockpit design, prevented the aircrew from fully exploiting the aircraft's performance capability.

During the last decade the need for human factors involvement in the design of the interface has been recognized and piecemeal improvements implemented, both at display component design and cockpit integration level. However, it should be remembered that cockpits are still designed by engineers, (albeit using human factors design recommendations), and not by the human factors specialists themselves. At first sight this difference may seem slight, in practice it can be critical.

DESIGN BY COMPROMISE.

The cockpit design process follows the same pattern as any system in the aircraft. Conflicting requirements of performance, cost and development time-scale are juggled to produce a compromise which promises the best return for the development risk involved. Unlike any aircraft system, the cockpit has man as the primary operating function and therefore the design process includes factors not normally part of an engineering discipline. However, the physical design of the cockpit interface is an engineering task, carried out in an engineering environment and dominated by personnel with an engineering discipline. Company aircrew, armed with "hands-on experience", will provide the subjective operational input and since they can argue that it is they

that take the ultimate risk, they have an undisputed influence on the design. The industrial human factors specialist is not so fortunate, for within the environment of "compromise design by strength of argument" he can be at a distinct disadvantage because the foundation of his discipline is abstract. Against the engineer's industrial pedigree of proof by theory and measured practice, he can only put forward recommendations based on isolated research, or general philosophical arguments based on collective theory and subjective experience. Against the crew's "front end" argument, he can only plead consideration for susceptibility of human senses to misinterpretation and the non-representative nature of experimental aircrew with respect to the end user population. In a three cornered industrial design debate where compromise is demanded and finance has the casting vote, human factors losses are disproportionately high compared to the gains. Once production is underway, modification, due to unpredicted design problems or requirement changes, are sought on a minimum-cost, minimum-programme upset basis, with aircrew under increasing pressure to overrule human factor considerations with an "undesirable but acceptable" seal of approval.

The engineering pedigree of the aircraft industry has developed because the discipline is able to use absolute and recorded measurement criteria. The process of theoretical studies followed by manufacture and practical measured evaluation has produced a closed loop learning process, which over a period of time permits the knowledge gained in one project to be extrapolated to the next. Human Factors, because it has few absolutes and as yet lacks a practical means of measuring performance, is unable to establish the functioning closed loop learning process and hence fails to develop a respected pedigree. The Human Factors influence on the design of the cockpit interface is therefore a short term affair because the discipline is, in practice, ill-equipped to withstand the rigours of a cost-conscious industrial life.

AIRCRAFT PERFORMANCE.

The aircrew working task in a modern combat aircraft is complex and presents the human factors researcher with problems when attempting to quantify performance. The trend has therefore been to concentrate research on isolated aircrew tasks with the hope that the resultant recommendations will operate collectively. Unfortunately, because human factors research funding and systems development funding have invariably the same origin, much of the human factors research is also systems or hardware specific. The result is that interface performance values for one system will not relate to another or will collectively contradict. In terms of the individual systems this may not be a problem; in terms of an integrated approach to the cockpit, it most certainly is. The effects of cockpit design on the overall aircraft performance are impossible to isolate in practice, although an indication as to its influence may be extrapolated from aircrew error accident statistics.

The need to keep a national airforce in a state of readiness for war time operation requires that both the training of personnel and the development of aircraft is an on-going evolutionary process completed within the confines of a peace-time environment. Accidents resulting in the loss of the aircrew and / or aircraft, due to the need to train, are therefore considered as an unfortunate but inevitable occupational hazard. Providing the number of losses per flying hour are low and common causes not too repetitious, the condition is considered broadly acceptable within the culture of a particular airforce.

An examination of the accident statistics from one national airforce for the last twenty years of combat jet operation, has revealed that over this period, accidents attributed to aircrew error, as a percentage of all causes, has remained almost constant at 50% even within generally improving loss rates. Unlike the majority of "other causes" where a single event or condition can result in the loss of the aircraft, crew error accidents are inevitably the result of compound conditions, where error or misunderstanding regarding the aircraft or environmental state leads the crew into false assumptions and actions which, combined, result in further error and eventually an irrecoverable situation.

Examination of the individual accident reports will produce numerous similar statements implying degrees of human failure, typically, the mis-reading of instruments, the failure to recognize warning conditions, disorientation, and engrossment in apparently trivial tasks. Taking a different view-point these statements can be re-written to imply an interface performance failure, ie. instrument presentation ambiguous, warning presentation not sufficiently attention-getting, data presented in an inappropriate format, etc. True, in the pure cold light of retrospect and in the safe environment of terrafirma, the progression to error may seem inexplicable or even inexcusable and the interface performance more than adequate, but in the real-world situation without foresight, how might the interface performance, or rather lack of it, assist the error progression or fail to arrest it ?

A relative, though admittedly questionable, indication of the effect can be produced by assuming that all crew are equally susceptible to error and comparing the aircrew error accident records of two specific aircraft performing similar roles. Taking the

same national air force over the same twenty year period and two specific aircraft, the percentage of accidents attributed to aircrew error are 35% and 65%, respective. Thus it could be argued that in the case of the latter a high percentage of the crew error was in part due to inadequate interface performance. The authors recognize the simplicity of the above statistics and the comment it is likely to produce; however, if viewed as a relative indication rather than an absolute statistic, the point will justify further thought. If a percentage of aircrew error accidents can be attributed to poor interface performance, and these must represent the extreme cases, then how much is the overall capability of the aircraft, as a weapons delivery platform, being degraded because the crew are not communicating efficiently with the aircraft and vice-versa ?

REDUCED DEVELOPMENT RISK.

The previous paragraphs have dealt with the effect that human factors involvement, or rather lack of it, may be having on the aircraft as a functioning weapons delivery system. It is now necessary to examine the implications of increased human factors involvement, in terms of the probable cost-effectiveness derived by the manufacturer.

To survive in business, the manufacturer of any avionic component, be it a display unit or the cockpit as an integral part of an aircraft, cannot afford to support a more rigorous human factors involvement unless there is a corresponding reduction in development risk and with it a potential cost saving. Therefore any human factors approach, hoping to gain a greater influence in cockpit design, is much more likely to succeed if it recognizes the value of the engineering discipline approach and operates within its confines. At first sight this would appear to be a difficult hurdle for the human factors researcher to manage, in practice it can be remarkably easy given co-operation on both sides. The authors of this paper come from radically differing disciplines, avionics engineering on the one hand, human factors psychology on the other, however, by combining the experience of both in a co-ordinated effort they are successfully influencing future cockpit designs with a "human factors design tool" generated specifically for engineers, which not only provides for a more successful cockpit but promises shorter and more cost effective development times.

HUMAN FACTORS DESIGN TOOLS.

The principle of the "human factors design tool" was generated to imply any absolute measurement system or mathematical process involving human sensory or psychophysical emulations which would aid in the prediction of the man machine interface performance. The "tool" may be an existing system, the CIE 1931 and 1976 Colour Systems being an example or one generated to perform a specific task. However the outputs must be in a form which can be recognised by or integrated into an engineering discipline.

Human Factors Design Tools are therefore engineering tools which permit selected aspects of the interface performance, including the human element, to be evaluated in absolute terms, without physical hardware, environment or aircrew. At initiation the process need not be exact or comprehensive, provided it has an absolute foundation and the limitations are recognized. Performance predictions carried out prior to equipment manufacture can be validated after build, by objective evaluation using experienced aircrew and qualified environment. Repeated predictions and validation exercises carried out during the development of an aircraft project produces a closed loop learning process, where limitations and errors in the "tool" can be identified and further research initiated. Using this combined Human Factors / Engineering approach, has the advantage that the simplistic "tools" can be used and developed inside the industry, with Human Factors research feeding in up-dates and improvements as they develope. The power and accuracy of the "tools" is an accumulation effect with the experience gained in one aircraft project being directly applicable to the next.

The cockpit man machine interface is complex in the extreme and could never be covered by one massive predictive design tool or even a multiple set, therefore the authors do not see the "Human Factors Design Tools" directly replacing subjective evaluation by experienced aircrew, but given time, they could dramatically reduce the number of evaluations necessary by increasing the probability of first time success. Recognizing this fact, the authors concentrated on one sensory interface, the visual system, and then only one aspect of that system, the ability of the crew to detect cockpit presented data under the range of ambient lighting conditions expected in the military aircraft environment. The historical development, practical application and future possibilities of this "Visual Interface Design Tool" is described here, both as a demonstration of the technique and as a demonstration of the influence a combined Human Factors / Engineering approach can have.

VISUAL INTERFACE DESIGN TOOL.

Over the last ten years, the use of emissive display devices in the form of cathode ray tubes has highlighted the difficulty in predicting legibility under various ambient lighting conditions. This, coupled with the introduction of colour, NVGs, helmet mounted sights and eye protective optics is now forcing display designers to consider all the cockpit display devices as an integral system, rather than a number of discrete equipments. Regrettably, until very recently, few designers have been prepared to admit that this is so.

In 1979, two independent and isolated UK research programmes were initiated, one within the Royal Aircraft Establishment at Farnborough, the other within the Aircraft Manufacturing Industry at British Aerospace Warton Division. RAE recognized the potential problems associated with the introduction of "Colour" in the cockpit and sought means of proving its value, whilst BAe, faced with existing monochrome airborne display problems, sought means to define visual performance in more precise terms. Although their aims and motives were different, both groups sought a process by which display devices could be evaluated at an early stage of concept as to their ability to convey information, both rapidly and unambiguously, to the pilot under all the various viewing conditions predicted. The avenue of investigation taken in each case was the mathematical modelling of the various power spectral distributions involved in the visual performance chain.

Work progressed independently until late 1981, by which time two separate but almost identical modelling programmes had been developed, one in BAe on a Mainframe Computer, the other within the RAE on a Microcomputer. The modelling processes operated on stored spectral data associated with the optical properties of all materials incorporated in the various display options proposed, together with the properties of the illumination, either natural or artificial, since both emissive and passive display devices are seldom used in zero illumination.

Details of how this might be achieved in were first published in 1982 (ref.1) and the concept was shown to be practical in 1981 at BAe Warton when a monochrome display filter was optimised for high ambient lighting conditions as part of the Tornado development programme. The concepts formulated are briefly re-stated here for clarity. In Fig.1 a typical cockpit display viewing configuration is simply portrayed. Within this configuration are included elements representing the emissive ambient illumination (I1), the head-down display (E1-3,F2 & F3), along with the filtering properties which may be attributed to the aircraft canopy (F1) and helmet-mounted filter (F4). Within the computer, all these systems components may be stored in terms of their power spectral properties. Within Fig 2. these spectra are indicated to the left of the diagram; although they are shown as three discrete types of information, in concept they are identical and represent a set of similar structured computer files which can be easily added and multiplied together. This latter operation permits the designer to fabricate, within the computer software, alternative display configurations from either existing or theoretical materials. The software computes power spectra which would arrive at the pilot's eye and presents them to the designer in tabular or graphical form. Such data are frequently difficult to interpret in terms of how they would appear within a display image; however, specialised software may be used to realise the additional elements within Fig 2. to create chromaticity coordinates which may be precisely presented for visual inspection, on a calibrated colour terminal. A full description of the capabilities of the software has already been published (ref.2)

The aim of restating this procedure is to indicate how a hardware design problem may be converted into relatively simple software capable of being hosted on a small microcomputer. The fidelity of such a procedure is easy to establish by the simple process of measuring the properties of individual components and their combined effect, storing the component data, calculating their combined effect and comparing the later data with those realised by measurement. Experience obtained whilst carrying out practical design problems has indicated that although the software does not return perfect results, it is sufficiently accurate for most practical design problems. Any inaccuracies are negligible compared with the major errors created in the absence of the design tool.

One major criticism of the procedure is that either it relies upon an expert to interpret the numerical print out, or requires a subjective evaluation to be carried out by the design team at the colour terminal. Unfortunately, neither can accurately take into account the substantial change in eye adaptation that will occur due to ambient illumination. In principle this adaptation can be produced by optical simulation of ambient on a device proximal to the terminal but in practice this is difficult due to the size of adaptation field required and the large number of varied ambient geometries and absolute levels to be considered.

To overcome these criticisms it was deemed necessary to generate a psychophysical data base which would allow the designer to interpret the numerical output of the software, taking into account the eyes ability to perceive luminance and chrominance contrasts produced by symbology of various shapes and sizes. Such data were not readily available from existing published reports, consequently, to fill this void a joint

research programme was initiated in 1982, which used a large lighting facility in conjunction with both aircraft and laboratory display equipments, to obtain data from numerous human observers. As a result of this research it is now possible to cascade the original software, manipulating the physical materials, with additional software containing weighting functions for the sensitivity of the "average" human eye under various viewing conditions. The result is a capability to be able to accurately predict not only the performance of existing systems but also the combined effect of display and perception and consequently the detailed design specification future devices must fulfill, if they are to operate satisfactorily within the aircraft environment. Figure 3. shows the current model configured for colour CRT display predictions, in an cockpit high ambient lighting environment, where the PJND (Perceived Just Noticeable Difference) performance value of a specific target can be determined from the format dimensions and red, green and blue gun bit drives. (ref.3)

EXTENT OF CURRENT APPLICATION.

Although both the initial software development and the subsequent laboratory trials were conceived to aid in formulating requirements for both the image formats and display hardware of colour cathode ray tubes, it was rapidly realised that inherent within the software was the capability of emulating alternative display technologies. Over the past two years this capability has been successfully employed to investigate numerous display devices and associated optical components including; monochrome/colour cathode ray tubes, liquid crystal matrix displays, contrast enhancing filters, illuminant filters, diffractive optic components and dichroic materials. The software is currently being employed to optimise colour display formats, determine the compatibility of cockpit displays to night vision goggle operation and evaluate the implications of using optical protection visors with both outside world images and cockpit display systems.

THE IMMEDIATE FUTURE.

Despite having overcome many of the deficiencies of the "design tool" by incorporating psychophysical data, the extensive time-consuming laboratory studies necessary to acquire such data have prevented the complex effects of image geometry to be fully represented within the calculations. Work is currently underway to incorporate algorithms devised from previous investigations within the industry (ref. Paper No.12 of this Symposium). This addition will enable the designer to consider not only the luminance and chrominance capabilities of display options but also to appreciate the degradation of visual performance due to the spatial and dynamic noise inherent within the display.

Throughout the development programme, great care has been taken to ensure portability of the software to make it generally available to designers. To achieve this latter objective, all current software is microcomputer based and the software package tailored to run efficiently. It was assumed that portability resulted from the low cost of purchasing specific hardware, rather than from flexible (complex) software capable of running on multiple machines. As the programmes are asked to perform more extensive calculations and the spectral data base library expands beyond the limits of the existing hardware, the next generation of software may require a more powerful host processor and/or the use of a nationally-available mainframe network. Currently, selected industrial users within UK are extending the range of applications, which in turn is causing a substantial library of materials to be established. Hopefully, the near future will see a rapid growth of this library, partially due to the increased use of computer-controlled spectroradiometers in measurement laboratories.

Although the primary objective was to provide a "design tool", one of the secondary uses to which the tool is being applied is the derivation of provisional design standards. To this end, BAe Warton Division is in the process of establishing a set of Company Standards in support of the modelling process, in the hope that this will lead eventually to National Standards for the industry to which design engineers can refer when specifying visual performance requirements. The original intention was for the model to provide simple numerical predictive values but it was realised that this alone required considerable skill and an extensive appreciation of the complex interaction of display parameters on behalf of the user. This latter skill may well lie beyond the expected level of competence of some design engineers; therefore a benefit the software could provide is to incorporate within its structure suitable algorithms to indicate the ability of the design to comply with predefined performance figures or standards.

CONCLUSIONS.

In our well-known fairy story, Cinderella proceeds from rags to riches by being good and having a Fairy God Mother with magical capabilities that would be the envy of any aircraft production manager. Our real life Human Factors Cinderella has no magical benefactor to lift her from the lowly position she presently occupies in industry, to one her potential capabilities deserve; therefore the battle for recognition is her own and it will not be an easy one. Human Factors has much to offer the aircraft industry both in the development of a better and more effective product for the customer and in its potential ability to save costs and development time by reducing the trial and error procedures still prevalent in the design of the man machine interface, but it is time she got up and did something positive to achieve it.

Human Factors research for Human Factors sake is no longer justifiable in an industry as cost-conscious and competitive as the aircraft industry. Human Factors is no longer a "science of interest" protected by the clean environment of the laboratory and shrouded in academic mystery. Human Factors is the new science of industry and as such must be prepared to fight and survive in that world without favour. The development of the "human factors design tool" for engineers described in this paper is only one way in which the cockpit design can be influenced, albeit that influence is small. However it is a positive step and once established will be difficult to erode, because it has a foundation of absolutes and is in a language the engineer understands.

Within the aircraft manufacturing industry there are a small but growing number of engineers and human factors specialists who both recognize the need and support the argument for a greater Human Factors involvement in design of the cockpit man machine interface, but whose attempts are too often frustrated because they fight without support. With the kernel of enthusiasm established in industry and the shift of cockpit design responsibility brought about by the aplication of systems integration, an opportunity now exists for large scale co-operative research, with Human Factors and Engineering collectively working towards integrated cockpit interface designs, based on integrated Human Factors design criteria, derived from integrated research programmes.

If this paper achieves little else, both authors hope that it has demonstrated that, given a reasonable degree of understanding and co-operation on both sides, collective research is both practical and potentially more cost effective than isolated research, because it relates directly to the "real world" industrial environment, produces results more in line with the industrial disciplines, and is therefore more likely to influence the manufactured product. Who knows, it might just be the catalyst to trigger the change of our poor Cinderella into the Princess Discipline of Cockpit Interface Design.

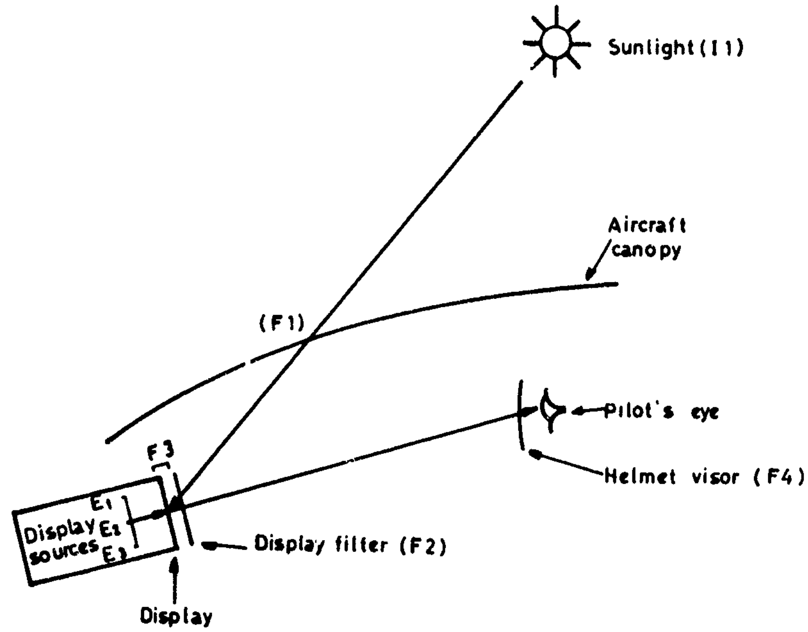

FIG. 1 SCHEMATIC OF TYPICAL AVIONIC DISPAY CONFIGURATION

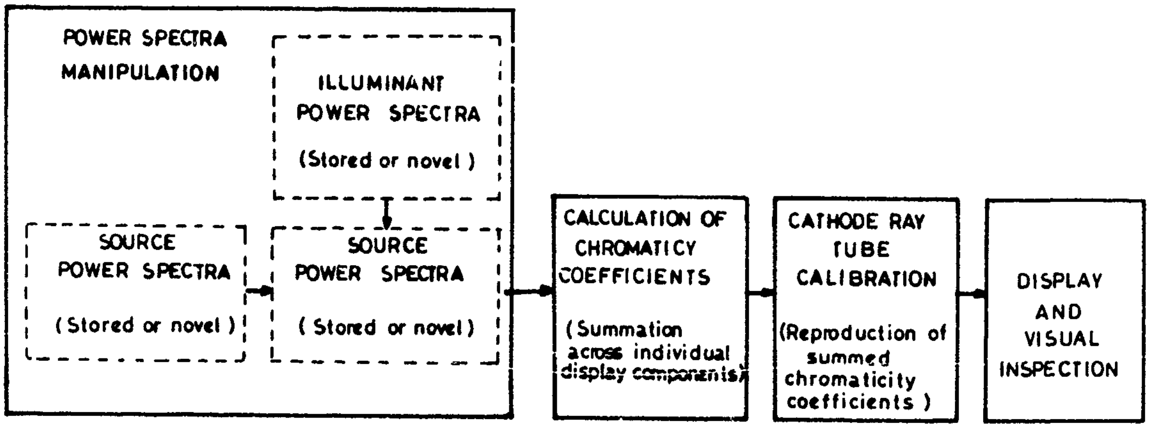

FIG. 2 CONSTITUENT COMPONENTS OF SIMULATION

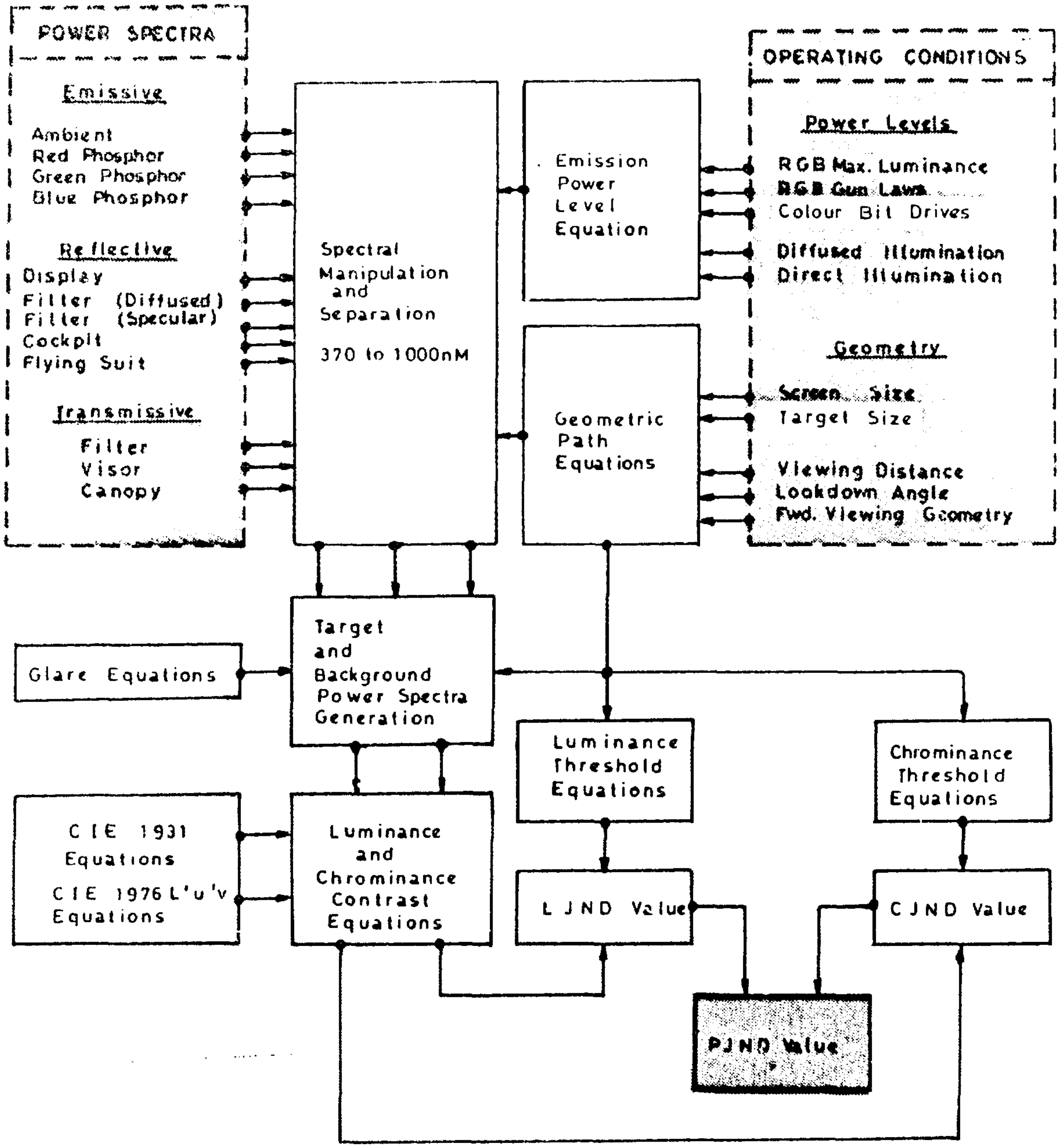

FIG. 3 VISUAL INTERFACE MODEL

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DISCUSSION
Papers 25–26

25. Mr Hulme - UK - Visual Difficulties Associated with Future Windscreen and HUD Integration.
26. Mr Ken Martin - UK - Human Factors: The Cinderella Discipline in Cockpit Interface Design.

Brennan UK: Perhaps you could tell me why we have windscreens where the geometric optical standard is so bad? Is it too expensive, or is it too difficult to make better windscreens?

Hulme UK: The windscreens that we have measured show that there is a great deal of variety, particularly in flat windscreens and this needs to be improved. In curved windscreens we believe that there are some difficulties, particularly as the windscreen gets thicker, in maintaining the optical quality. For instance bird-strike resistance is a problem and we have been asked to increase the thickness of the windscreen to overcome it and at the same time as we increase the thickness of the windscreen we increase the optical deviation through that windscreen.

Brennan UK: Do you have any values for the optical deviation?

Hulme UK: For a 1" thick windscreen you are talking about +2 milliradians. Now this means that as long as that is known, the HUD can be balanced to that, to get an accurate combination of the two systems.

Marshall UK: In the situation you cite with conventional HUDs, it is relatively easy to control collimation to give you the milliradian accuracy that you want. When you come to curved windscreens, F16 type windscreens, you are now talking about also wanting wide angle HUDs which come from diffractive optics and the capability they give you. I think you are talking about a milliradian accuracy that you are not going to achieve. Even if you can correct for the cylindrical inaccuracies of the windscreen itself and that is done on the F16 HUD as you probably know, you then introduce the disparities which occur with movement of your head within the motion box of viewing the HUD. Although they are calculable they cannot be taken out because moving your head introduces an error of the order that you are trying to eliminate, so you have an insuperable problem.

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14. Abstract

Vision is the pre-eminent sensory channel through which the aviator obtains information necessary for the control of his aircraft and the execution of his operational role. Recognising this to be important, all reasonable and practical means of enhancing and protecting vision should be adopted. The papers selected for the Aerospace Medical Panel's Symposium in Athens, Greece from 22 to 24 April 1985 considered not only systems for visual protection and enhancement but also addressed the basic physiological and pathological mechanisms underlying existing and future solutions.

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